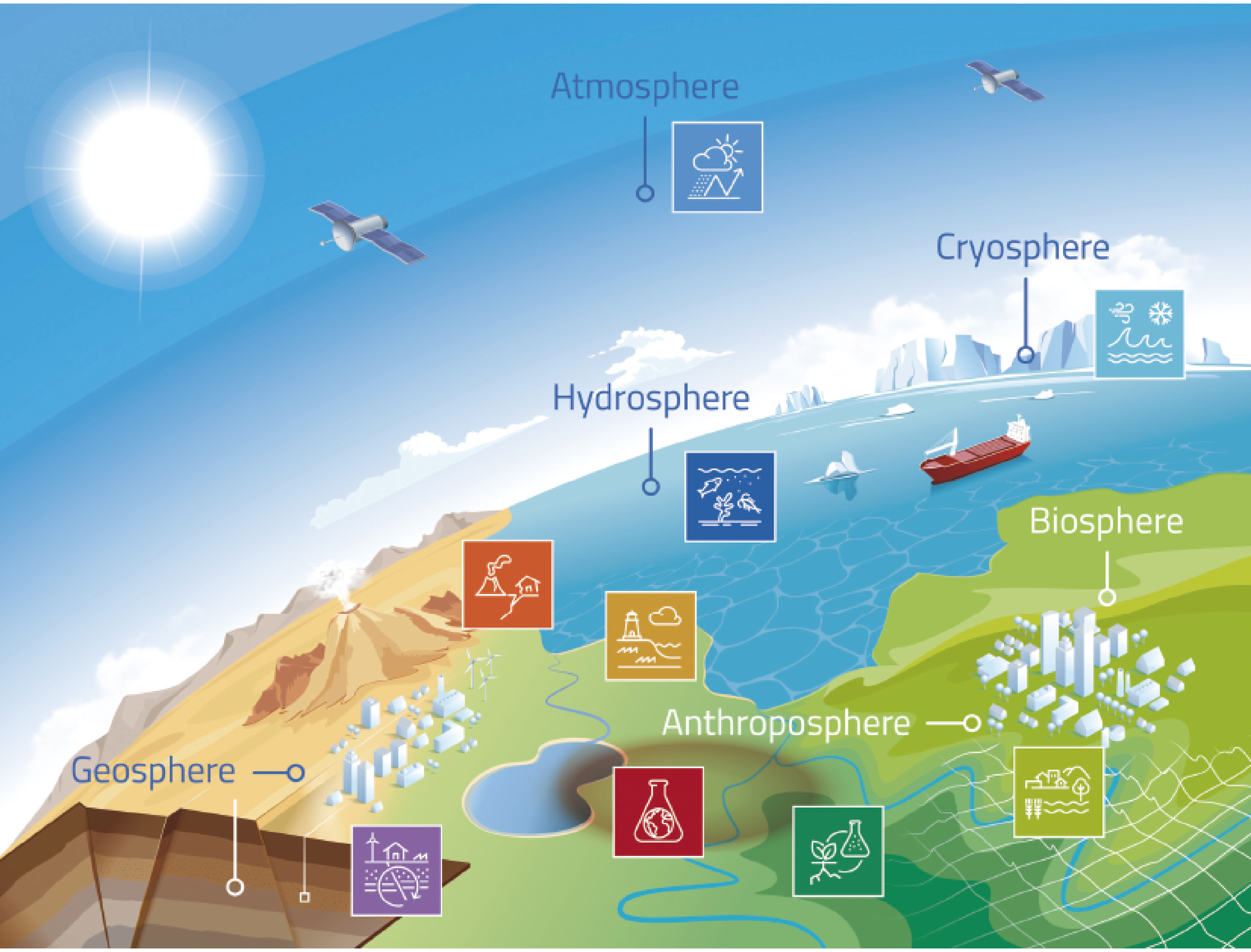
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Proposal for the Helmholtz Research Program

Changing Earth – Sustaining our Future

Research Field EARTH & ENVIRONMENT
2021 – 2027



4 Overview of the Program 'Changing Earth – Sustaining our Future'

The Program 'Changing Earth – Sustaining our Future' will contribute to a holistic understanding of Earth system dynamics, interactions and feedback mechanisms across Earth's compartments through time and space. Our previous results have already demonstrated the challenges of an overexploited Earth system at the brink of irreversible damage. We will unify formerly separate Programs to link expertise and infrastructures and to generate and communicate systemic knowledge to decision-makers in politics, economy and the broader society. **This Program will thus provide actionable knowledge needed for a sustainable management of planet Earth.**

Brief Summary. Humankind depends on the space, resources and vital functions of planet Earth, but increasingly overexploits these. Earth System Science shows that pivotal functions and services which emerge from the interplay of Earth's various components are seriously at risk. Planet Earth is a dynamic and highly delicate system that cannot be understood, let alone managed, without considering the interdependence of its components and compartments. Global change processes therefore drive an urgent demand for **systemic solutions** that minimize the negative impact of a warming climate, species loss, degradation of environmental health and related environmental problems. Science is asked to provide viable options for safeguarding future societies from rapid or unexpected change and for exploiting Earth's resources in sustainable ways. The challenge is thus to generate and provide fundamental knowledge (advanced understanding of the Earth system) and applicable know-how (predictive capacity as well as technical and management options). These outcomes are required to support society, policymakers and economy in taking critical decisions in the face of inevitable change and natural hazards and with the perspective of providing a sustainable, livable environment for humankind and the biosphere as a whole.

This challenge and the complexity of interacting compartments of planet Earth, including its interactions with humanity, motivates the Research Field Earth & Environment (RF E&E) of the Helmholtz Association to bundle its competences in the fourth period of Program-oriented Funding (PoF IV) in one common Program. The Program 'Changing Earth[1] – Sustaining our Future' will thus pool the expertise of more than 1,200 scientists – reinforced by doctoral students, post-doctoral students, technical and administrative personnel – from seven Helmholtz centers.

Integration into one Program will allow

- systematic cross-compartment research towards the development of systemic solutions to ensure the realization of our mission,
- interlinking, harmonization and coordinated utilization of its unique facilities for laboratory and fieldwork, Earth observation, computing and data science to make the best use of the world-class large research infrastructures of RF E&E,
- the implementation of improved and joint instruments for science synthesis, communication, and participatory transfer that will promote the generation of systemic outcomes beyond scientific publication to promote societal transformation and
- forming a generation of scientists from seven research centers in a joint spirit of openness for solution-oriented Earth System Science bridging the Earth's spheres and scientific disciplines.

[1] The double meaning (passive and active) is intended.

Nine thematic Topics constitute the Program's backbone. Selected Cross-Topic Activities (CTAs), Cooperations across Research Fields (CARFs)[2] and Alliances with partners outside Helmholtz account for the necessary integrative approaches to investigate the interwoven state of Earth system and environmental[3] processes. By increasingly aligning and integrating these activities during the funding period, the Program will command an unparalleled combination of scientific expertise and advanced research and data infrastructure.

Presently, the centers of the RF E&E organize their Earth System Research into six well-attuned and successful Programs that reflect six main components of the Earth system. All Programs have been rated 'outstanding' with regard to scientific expertise, productivity, and international impact. We expect the new joint Program to become a pioneer for urgently needed, more widely integrated Earth System Science delivering even more systemic and problem-oriented outcomes. It is a response to the inextricability of natural and increasingly anthropogenic processes in the different compartments of the Earth system.

International and National Roadmaps and Research Infrastructures. The research Program 'Changing Earth' is motivated by a broad scientific consensus that the present management of our planet is neither sustainable nor adequately adapting the society to the ongoing change processes and associated hazards. International political roadmaps have taken up these substantial concerns. The UN Sustainable Developments Goals[4] provide important generic and specific reference points for all Program Topics (for details see there). The United Nations Framework Convention on Climate Change (UNFCCC), better known as the Paris Agreement on a <2°C target for near-surface atmospheric warming, has similar overarching importance and forms the basis for one of the central scenarios considered across all relevant Topics of the Program.[5] The IPBES report 2019 has concluded that every 8th species on Earth is endangered by unsustainable land and ocean use, and by climate change. These findings and a number of national targets derived from them have also informed the Strategic Guidelines (FoPoZ)[6] of the Federal Ministry of Education and Research for the upcoming Program period. Other initiatives, such as the Sendai Framework for Disaster Risk Reduction 2015–2030, set out priorities for mitigating against the impact of (sometimes increasing) natural hazards on society,[7] for which an enhanced understanding of the Earth system within the context of the processes behind natural disasters is essential. Taken together, these frameworks form the political underpinning of the science in this Program. Like its predecessors, this Program will provide important contributions to the United Nation's bodies of science synthesis, namely IPCC and IPBES. With respect to Germany, the Research for Sustainable Development (FONA3)[8] Program, the National Climate Protection and Climate Adaptation Plans, the National Bioeconomy Strategy as well as the upcoming National Earth System Modeling strategy anchor the Program into nation-wide research strategies.

The Program covers a wide range of strategic aspects for providing scientific knowledge to preserve the Earth system as a suitable habitat for humankind, to encourage a more responsible stewardship of the ecosystems and to provide a more profound understanding of the atmospheric, marine and geosystems, which jointly control and reflect the behavior of the Earth system. Present-day Earth System Research relies heavily on advanced and diverse research infrastructures, which need to be strategically enhanced and integrated, to provide improved and rich Earth system data. The strategies underlying the National Roadmap for Large Scale Infrastructures[9] account for this. Besides operating and providing large user facilities of the LKII funding line supporting its targets, the Program coordinates networked national and international infrastructure collaborations and contributes to shaping the European Research Infrastructure landscape.

[2] CTAs and CARFs are subsumed as Cross-Cutting Activities (CCAs).

[3] For the sake of brevity Earth system and environmental (processes, science or research) will be shortened to 'Earth system' in the following.

[4] The SDGs 2 – Zero Hunger, 3 – Good Health and Well-Being, 6 – Clean Water and Sanitation, 7 – Affordable and Clean Energy, 11 – Sustainable Cities and Communities, 12 – Responsible Consumption and Production, 13 – Climate Action, 14 – Life Below Water, 15 – Life on Land and 17 – Partnerships for the Goals are of particular relevance for this Program.

[5] Cf. research objective #10 on page 41.

[6] Cf. separate document 'Strategic Guidelines of the Federal Ministry of Education and Research'.

[7] See https://www.unisdr.org/we/coordinate/sendai-framework.

[8] See https://www.fona.de/en/index.php.

[9] See https://www.bmbf.de/publikationen/?E=1887.

5 Research Program

5.1 Objectives and Strategy

Challenges. Scientific analysis of the status and the perspective of the Earth system demonstrates that business-as-usual practice is not sustainable and might result in a catastrophe for civilization. The rate at which the human population is growing and consuming Earth's resources outpaces the rate at which the Earth system can balance or replenish them. The growing imbalance between demand and supply, and the fact that many materials follow a linear path from resources via products to waste results in a plethora of problems. These include climate change and its short- and long-term consequences, environmental pollution, soil degradation, the lack of clean water, risks to food and energy security, the shortage of safe, habitable living space, as well as the loss of biodiversity and the ecosystem services provided. Importantly, these global problems have regional and local manifestations. It is thus of utmost importance to provide knowledge at the scales where mitigation and adaptation measures need to be taken. For instance, the increasing populations, urbanization, growing dependence on technological infrastructure, and uncertainty associated with climate change are increasing the risks associated with natural disasters.

Historically, the states of cultural development and technology have limited the human population size and its environmental footprint. Key advances in agriculture, industrial production, technological advances in all sectors, and improvements in medicine have prompted population booms. Today, the boundaries of the Earth system as a whole have become the limiting factor for further societal development.[10] The impacts of human activities on the Earth system have reached such scales that they are affecting its functioning globally and can even drive geological and geochemical processes with repercussions on human wellbeing – observations that have led to the labeling of our geological era as the 'Anthropocene'.[11]

Broad international consensus exists that the present degree of non-sustainable actions and structures requires a shift of attitudes and practices of our societies. Here, Earth System Research has the chance – and thus carries an enormous responsibility – to reconsider the level of human influence that defines the Anthropocene as an opportunity for developing thoughtful, durable management of our planet. On the one hand, this requires the provision of essential scientific knowledge as to Earth system states, dynamics and tipping points in the past, present, and future as a basis for sustainable management options. On the other hand, it requires resolving the critical situation by demonstrating options for adaptation to now inevitable change and hardly controllable geological risks.

To meet the challenge of understanding the Earth system well enough for adequate management, the Program will pioneer a high degree of integration across its broad scientific scope. And – through its interdisciplinary and transdisciplinary approach – it aims to attain a substantial societal effect. To this end, the Program will conduct solution-oriented, systemic research within the context of five overarching grand challenges in line with the FoPoZ:

- **climate change** with an emphasis on the drivers as well as the impacts it will have on natural and human systems, including regional manifestations and extreme events,
- risks for human habitats and activities arising from **Solid Earth dynamics,**
- threatened **ecosystems, biodiversity and biogeochemical cycles** as foundations of vital ecosystem services,
- dwindling **natural resources** as the limiting factor for societal development globally,
- the need to preserve or achieve a good **quality of the human environment** with an emphasis on air quality, reduced pollutants exposure and livable, sustainable cities.

[10] Steffen W, Richardson K, Rockstrom J, Cornell SE, Fetzer I, et al. 2015. Planetary boundaries: Guiding human development on a changing planet. Science. 347(6223):1259885.

[11] Crutzen PJ, Stoermer, E.F. 2000. The "Anthropocene". Glob Change Newsl. 41:17.

Scientific Objectives. We have devoted a number of bottom-up and top-down scientific workshops during 2017/18 to planning the integration of the five Programs of the RF E&E and the Program 'Key Technologies for the Bioeconomy' presently affiliated with the RF Key Technologies. This resulted in nine Program Topics intersecting the former Programs. For this strategic proposal, each of the nine mission-driven Program Topics has formulated its scientific objectives contributing to the aforementioned challenges (cf. Topic descriptions). The Program as a whole has defined objectives of an overarching nature, to which it is committed. Taken together, these objectives constitute the scientific mission of the Program and serve both to integrate our scientific activities and as a measuring stick for their impact with regard to societal benefits.

Scientific Objective 1: Provide improved quantitative forecasts of weather, atmospheric composition, and seasonal extremes by extending the practical limits of predictability based on advanced modeling, data assimilation, and observational capabilities. The focus will be on regional to local scales as the basis for better informing emergency measures and climate change adaptation (T1 T2 T3 T4 T5 T7).

Scientific Objective 2: Develop science-based scenarios for effective mitigation measures taking into account climate drivers as well as biogeochemical cycles, including critical fluxes between Earth system compartments (all nine Topics).

Scientific Objective 3: Underpin climate adaptation action with science. The focus will be on systemic solutions and their implementation (T1 T4 T5 T7 T8).

Scientific Objective 4: Provide a new understanding of the drivers of geo-hazards (including cascading phenomena) and their impacts, and develop the means of providing tailored forecasts on local and global scales (T1 T2 T3 T4 T5 T8 T9).

Scientific Objective 5: Mitigate urban climate change risks and increase the adaptive capacities and resilience of urban areas. This encompasses developing proposals that i) enable urban spaces to cope with multi-hazards and climate risks, ii) provide healthy environments for their inhabitants, and iii) develop novel technological and system solutions for infrastructure management (T1 T3 T4 T5 T7 T8 T9).

Scientific Objective 6: Synthesize data, processes, and their multiple interactions, models, and forecasts as well as the theory of biodiversity change and the consequences for ecosystem functions and services. The main common target is to explore, derive, and design solutions for sustainable use of marine and terrestrial ecosystems under the conditions of global and climate change (T4 T5 T6 T7 T9).

Scientific Objective 7: Develop solutions for a more sustainable, climate-resilient, and climate-protective production and consumption contributing to food/feed and water security and quality. The focus will be on a nested approach optimizing biological resources for breeding and production systems with stewardship to terrestrial, atmospheric and marine natural resources and on sustainable land management in rural and urban areas (T1 T4 T5 T6 T7 T9).

Scientific Objective 8: Establish sustainable options with regard to the use of natural resources in demand by industry and society. The focus will be on solutions towards resourcing, production, and processing that may contribute to the vision of a circular economy by technical, social, and economic opportunities (T4 T5 T6 T7 T8 T9).

Scientific Objective 9: Organize coherent concepts for understanding and assessing the interaction between environmental pollution and human and ecological health across diverse settings to overcome current fragmented 'silo' approaches and provide options for solution-oriented management strategies towards sustainable chemical use in a non-toxic environment (T1 T4 T5 T6 T7 T9).

Scientific Objective 10: Synthesize insights from all nine Topics to a comprehensive, multi-sectorial picture of a sustainable future of humankind on an Earth that has endured substantial climate change (all nine Topics).

In their entirety, these objectives set out to lay the path towards a future Earth that can sustain human society and the biosphere as a whole. They serve as guides for Program-wide systemic research and outcomes, including science synthesis, agile Program development, as well as the execution and initiation of Cross-Topic Activities and cooperation across Research Fields. Program-wide scientific workshops serving as think tanks will be devoted to each of these objectives.

Relevance. The relevance and urgency of the proposed research arise from the need for science-based knowledge and solutions to the societal challenges discussed earlier. Managing these challenges and risks not only requires a deep understanding of the interconnected processes of planet Earth as an integrated system but also options for mitigation and adaptation, including preparedness.

In January 2019, the World Economic Forum issued its World Risk Report[12] listing the following six Earth system and environmental risks among the top ten of the most likely and most consequential risks for 2019: extreme weather events, failure of climate mitigation and adaptation, natural disasters, man-made environmental disasters, biodiversity loss/ecosystem collapse and water crises. Because of such assessments and their dissemination in the media, and reinforced by first-hand physical experience, e.g., made during the Europe-wide droughts in 2018 and 2019, there is enormous public concern about the state of the human environment. The worldwide 'Fridays for Future' protests and the 'Science for Future' warnings with over 20,000 signatures are presently one of the most visible signs of wide-spread concern. A new report on a representative citizen poll in Germany on the state of the environment, public concern, and rating of political action published by the German Environmental Agency[13] shows the urgency of action. The frustration about perceived political inaction or even abnegation by some decision-makers, where rapid and responsible action should rather occur, is at an all-time high. Our joint Program responds to these concerns by addressing many of the challenges and translating them into forefront research, capacity building, and knowledge transfer.

Strategy and approaches to realize the Program objectives. The Program is committed to generate knowledge and provide viable options for the sustainable management of planet Earth and improved resilience of human societies and ecosystems in the face of natural and anthropogenic hazards. This commitment includes the aspiration that the development of options for action uses systemic approaches to minimize the negative side- or rebound effects. The RF E&E is outstandingly positioned to address several of the pressing and the long-standing problems of Earth and environment in systemic ways:

- It covers all compartments of the Earth system and has substantial critical mass for comprehensive Earth System Research,
- it has access to several hot spots of environmental change and natural hazard and maintains solid networks of local partners,
- it hosts an exceptionally broad spectrum of natural, engineering, socio-economic and data sciences,
- its network of excellent scientific partners complements the portfolio, closes gaps of expertise and has the potential to enhance the Program's scientific outreach,
- it commands a world-class scientific infrastructure in its institutes and deployed worldwide,
- its long-term funding perspective ensures the long wind required for Earth System Research and capacity building,
- it has over 15 years of experience in cross-center science integration within the frames of its past and present research Programs and
- it has a long record of stakeholder involvement in its research and dialogue-oriented and participatory knowledge transfer.

With all these elements for Earth System Science at hand, the challenge is to deploy and link them in ways to create benefit while ensuring a continued outstanding performance of its contributing parts. This is delineated by an overarching strategic objective which is in alignment with the strategies of Helmholtz, the RF E&E, and the FoPoZ for PoF IV:

Strategic Objective: Integrate, coordinate, and harmonize the Earth System Research conducted in the seven thematically complementary centers of the RF E&E to maximize its quality, efficiency, vigor, visibility and societal benefit.

This objective shall be achieved by a fundamental reorganization of six predecessor Programs which had already successfully enhanced our competence for interdisciplinary cross-center collaboration. The new Pro-

[12] See https://www.weforum.org/agenda/2019/01/these-are-the-biggest-risks-facing-our-world-in-2019/.

[13] See https://www.umweltbundesamt.de/en/press/pressinformation/environmental-awareness-study-2018.

gram is based on binding and dedicated contributions of all seven centers, which contribute to mission-driven Program Topics according to their key expertises. The 'One Program' structure is thus the major instrument of the RF E&E to close ranks and develop a coherent and comprehensive research portfolio while expanding the scope and momentum of the generation of scientific and actionable knowledge. The scopes of the nine Program Topics (cf. Topic descriptions, p. 47) differ from the relatively strict sub-compartment perspectives of the predecessor Programs. The new Program Topics all address directly major scientific challenges reaching beyond individual compartments of the Earth system. The Topics encompass all scientific personnel of the RF E&E except a small group of specialists who operate the large user-facilities. Cross-Cutting Activities (CCAs) distinguished as internal Cross-Topic Activities (CTAs), and Cooperations across Research Fields (CARFs) bring leverage to elements from several Topics and themes from other Research Fields, thus forming the second dimension of Program integration. The establishment or conclusion of CCAs during the Program period also represents an important element of programmatic flexibility complementary to Topics, which serve as thematic platforms for the entire Program period. The combination of Topics and CCAs ensures that fruitful past collaborations within and across centers continue while a substantial number of new links emerge, which integrate complementary – albeit formerly separated – expertise as well as fragmented contributions to overarching scientific challenges. Importantly, the scientific portfolio was developed in due consideration of the Program member's roles in numerous excellent partner networks outside of Helmholtz to establish a strategic integration of its activities at the level of Helmholtz as well as in the national, European and international arenas. The overarching strategic objective translates into a few structural objectives delineating its approaches and measures.

Structural Objective 1: Implement instruments and incentives removing institutional barriers between formerly separate research themes to encourage integrated bottom-up research initiatives, concept transfer, upgrading of scientific knowledge to systemic solutions and the creation of a corporate culture within the RF E&E.

Important first steps in this direction have already been made. The elaborate joint Program preparation involved an unprecedented extent of RF-wide scientific discussion, mutual exposure to the other centers' research subjects and approaches, transparency of the research portfolio of the entire RF E&E and led to a new acquaintance with colleagues from other centers. An important process will be the continuous transfer of these effects to the operational level of the Program, which has started with workshops and working groups. An important driver for cross-center collaboration will be our scientists' anticipation of benefits from newly accessible expertise, infrastructure, and access to research sites. Important instruments will be the operational sub-structures of the Topics, formats of SynCom, and incentives provided by an Innovation Pool. Transferable elements and themes that are relevant across the Program and function as attractors for cross-center interaction comprise:

- drivers of change,
- feedback mechanisms and the coupling of systems,
- processes leading to possible tipping points,
- dynamics of extreme events and their consequences,
- determinants of risk,
- prediction of Earth system and environmental dynamics,
- translation of global challenges into regional perspectives,
- opportunities arising from the digital revolution,
- technical, management, economic and policy options for a technological and societal transformation to sustainability and resilience, and
- responsibility for the transfer of outcomes to stakeholders in society and economy.

Structural Objective 2: Implement procedures for the strategic planning and management of research infrastructures aligned with Program objectives.

Research towards a better understanding of the Earth system and its components must be supported by the development of state-of-the-art research methods for observation, experimentation, modeling, and prognosis, underpinned by world-class research and data infrastructures. At the level of Helmholtz, this requires adjusting and enhancing our large-scale user facilities (LKII) and modular, smaller scale (LKI) infrastructures[14] to capture the temporal and spatial scales at which crucial processes take place, to enable the processing and interpretation of the large volume of data obtained and to develop, build and operate pilot and demonstration infrastructures to examine proposed solutions. The RF-wide integration of research will be underpinned by coordinated planning of research infrastructures for more efficient use of these resources and avoidance of redundancy. Important infrastructure decisions will thus be taken by the Management Board in consultation with the Program Board, and the latter will propose infrastructure adjustments and expansions to the Management Board. One tool are joint proposals for Strategic Investments (Helmholtz Program), another one are cross-cutting innovation themes such as the CTAs MOSES and Digital Earth.

Structural Objective 3: Develop and implement a seamless feedback loop of science dialogue and stakeholder (society, policy, economy) involvement, scientific research, science synthesis, and the transfer of technology and knowledge.

The Program ‘Changing Earth’ is motivated by the need to support the broader society, policymakers and the economy in taking critical decisions in the face of environmental change and by providing technical and management options for sustainable development. Scientific process understanding needs to be translated into recommendations for action, which in turn, need to be analyzed for their societal and economic consequences and feedback into the Earth system. In parallel, the scientific process needs to take up societal questions and economic needs and to analyze and communicate feedback to communities. All this requires the timely involvement of societal and economic stakeholders (politicians, industries, other societal groups). We will start a joint initiative and cross-cutting Synthesis and Communication Platform ‘SynCom’ that will be in charge of Program-wide synthesis and communication (see Ch. 1.4.1, p. 5). This includes the development of capacity and procedures (within Helmholtz and in selected key regions) for responsiveness to crises and political/societal inquiry. However, increasing the ‘readiness’ of scientific information and knowledge for societal usage (in analogy to the technology readiness) is a generalized obligation on all levels of the Program and a performance criterion. In practical terms, personnel and financial resources will be devoted to such activities, a commitment to these actions will be incentivized and valued, and their impact will be monitored. Metrics comprise the balance of the expenditure of personnel resources versus the number of institutionalized transfer activities in the categories ‘information and consulting,’ ‘stakeholder dialogue’ and ‘education and capacity building.’ The development of a catalog of meaningful specific metrics of impact, qualitative and quantitative, will be a task for the Program period. For science synthesis, the coordinated planning and integration of research is the major task as it ensures the creation of synergies and the provision of synthesizable knowledge. The Program has the unique chance to match the scopes of research integration and knowledge synthesis, i.e., base demand-oriented synthesis on broad-scope integrated research, an enormous advance compared to present-day post hoc science synthesis.

Preliminary work and Program preparation. In the 2018 Nature index of research institutions in Earth and Environmental Science, Helmholtz holds the second rank globally.[15] The new Program will thus build on a history of substantial output of strong science. The common Program proposal aims to continue, expand and integrate the successful work of five current Programs within RF E&E (‘Geosystem – the Changing Earth’; ‘Marine, Coastal and Polar Systems’; ‘From the Deep Sea to the Atmosphere’; ‘Atmosphere and Climate’; ‘Terrestrial Environment’) and the Program ‘Key Technologies for the Bioeconomy’ presently affiliated with the RF Key Technologies. As the outcome of in-depth quality evaluations between October 2017 and April 2018, the past scientific performance of all six Programs was rated ‘outstanding’. This top grading is both an encouragement and an obligation for further improvement. To illustrate this, some of the reviewers’ recommendations that will be implemented in the new Program, are listed in Table II-1, together with our measures and instruments.

[14] An overview of research infrastructures going beyond the constraints of this proposal will be available during the on-site evaluation.

[15] The Nature index is not normalized to the sizes of the listed institutions and therefore characterizes the absolute volume of scientific output.

5.2 Structure of the Program

The Program structure fulfills thematic (coherence and complementarity) and organizational (operability and collaboration) requirements. Nine research Topics (see Fig. II-3) and their project-type Subtopics form the structural backbone of the Program. Topics are designed for high thematic coherence, communicable missions, multidisciplinarity and complementarity across centers.

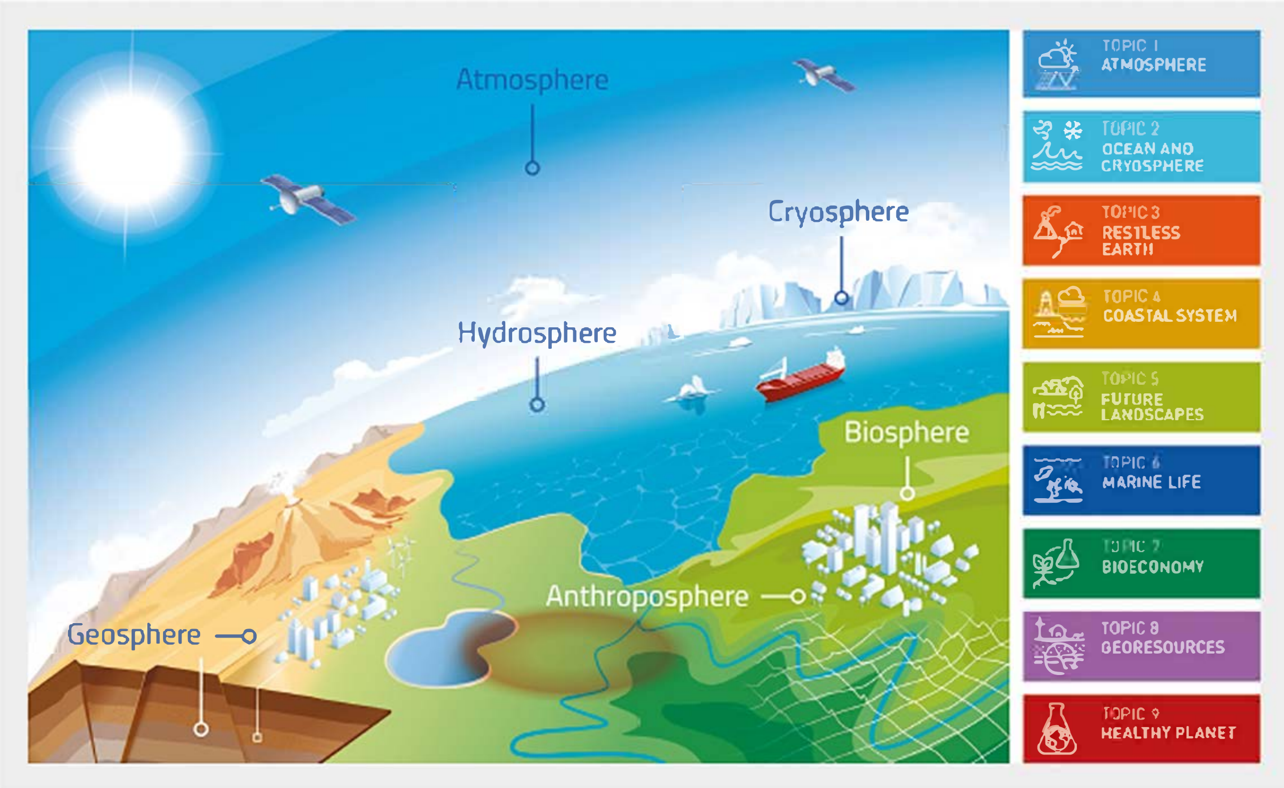


Fig. II-3: The scope of the Program 'Changing Earth' and its Topics at one glance.

2 Cross-Cutting Activities and Alliances

Cross-Cutting Activities (distinguished as CARFs and CTAs) and Alliances serve the overall objectives of the Helmholtz Association to bridge Research Fields, to promote thematic profiling and networking in the Research Fields and to strengthen and organize links with the German scientific community. Ongoing and planned Cross-Cutting Activities of RF E&E and partners comprise:

- Cooperations across Research Fields (CARFs)
  - Common research networks REKLIM and HI-CAM
  - Eight cooperations with other Helmholtz Research Fields
- Cross-Topic Activities (CTAs)
  - Observatories: TERENO and MOSES
  - Data and modeling platforms: Digital Earth (DE) and Earth System Modeling (ESM)
  - Planned Cross-Topic Activity: Extremes
- Science Alliances: DAM and DESA.

For ongoing CCAs, FTEs of personnel allocated by the Topics are indicated.

2.1 Cooperations across Research Fields (CARFs)

2.1.1 REKLIM: Regional Climate Change and Humans

with RF Aeronautics, Space and Transport | Coordinators: Klaus Grosfeld, AWI; Peter Braesicke, KIT

Running Time. The activity started in 2007 and will run through PoF IV.

Planned FTE (scientists) in PoF IV. AWI: 11; FZJ: 2; GEOMAR: 0,[16] GFZ: 1.5; HZG: 2; KIT: 6; UFZ: 2.

Objectives and Challenges. The Helmholtz climate initiative REKLIM is a research network of competence-driven modules. REKLIM produces and disseminates regional climate change information for societal use. The REKLIM research network works across disciplines (including social sciences), methods and centers,[17] and amalgamates regional observations, process studies and coupled model simulations with a focus on regional climate change and its relationship to humans. With its decade-long experience in cross-institutional collaboration, its research themes[18] enable linkages and syntheses with a clear focus on regional climate change.

Relevance and Strategy. REKLIM unites excellent scientists at various career stages with a particular emphasis on Ph.D. researchers. It addresses the complete chain from knowledge generation to action, enabling civil society to better approach climate mitigation and adaptation from the grassroots.

Involved Partners. AWI (T1, T2, T4, T6), FZJ (T1), GEOMAR (T2, T4), GFZ (T2, T5), HZG (T1, T4, T5), KIT (T1), UFZ (T4, T5, T9), DLR (RF Aeronautics, Space Transport; T1, T2, T5), HMGU (RF Health; T1, T9). REKLIM was directly funded with 8.25 Mio. € (plus the same amount mirrored in the centers) per year from 2009 to 2015. Thereafter, the funding was transferred into center budgets and allocated to REKLIM activities.

Approaches, Methodologies, Measures. REKLIM has developed to a well-balanced themed research network. The REKLIM research themes represent central aspects of regional climate change directly linked to the new Topics. Complementing CCAs include ESM with its focus on global simulations, with REKLIM providing a further regionalization. DE emphasizes data acquisition and data science that REKLIM will tailor for further

[16] No upfront allocation in PoF IV. However, the center will be an involved partner.

[17] See https://www.reklim.de/en.

[18] REKLIM research themes across Topics: 'Drivers and coastal impacts of sea-level rise', 'Coupled regional modeling', 'Extreme events across temporal and spatial scales', 'Atmospheric composition including greenhouse gases', 'Regional cultures of response to climatic change' and 'Land surface and its feedback mechanisms'.

regional applications. With the CTA TERENO, REKLIM pursues the analysis and integration of land surface observatory data into regional models. Interfaces to CARF HI-CAM concern the identification of driving mechanisms and the extension of impact chains and associated adaptation measures for societal actors in REKLIM.

Important Preliminary Work. REKLIM produced nearly 300 peer-reviewed publications and more than 30 Ph.D. theses since 2009. In 2014 the international REKLIM conference attracted 320 participants from 28 countries. Annual regional stakeholder conferences foster the dialogue with societal actors in Germany. REKLIM provides high-quality knowledge transfer,[19] e.g., meereisportal.de, the drought monitor and the regional climate atlas, and started a project for 'climate change and its impacts' in adult education in community colleges. The Helmholtz climate offices facilitate stakeholder interaction and the dissemination of scientific results.

2.1.2 HI-CAM: Helmholtz Initiative on Climate Adaptation and Mitigation

with all other RFs | Overall coordination and coordination of Cluster Adaptation: Georg Teutsch, UFZ; coordination of Cluster Mitigation: Daniela Jacob, HZG; coordination of Cluster Communication: N.N.

Running Time. 2019–2021, shall be continued in PoF IV.

FTE (scientists) from 2019 to 2021. AWI: 2; FZJ: 2.75; GEOMAR: 4; GFZ: 4; HZG: 6; KIT: 2; UFZ: 8; RF Health: 7; RF Matter: 1; RF Key Technologies: 1; RF Energy: 14.25; RF Aeronautics, Space and Transport: 5.

Objectives and Challenges. The extremely dry and hot summer of 2018 and the significant increase of hot years during the past two decades have enhanced the awareness of society and politicians for climate change and its impacts. In addition, the IPCC special report issued in 2018 illustrates that a 1.5°C global warming, i.e., 0.5°C less than the Paris Agreement, bears already considerable risks for life on Earth including humanity; but it also suggests that limitation of global warming to below 2°C compared to pre-industrial levels is possible. There are two perspectives and consequently modes of action to address this problem: i) mitigation, i.e., reduction of greenhouse gases to reduce global warming to meet the climate goals, and ii) adaptation, i.e., developing strategies and measures to cope with regionally specific effects of global warming to minimize unavoidable impacts and increase the resilience of ecological and technical systems. Both are part of numerous national and international research agendas and political strategies, which are regularly discussed and updated but as yet, seldom adequately implemented.

HI-CAM has three main objectives to close the identified mitigation and adaptation gaps: i) We will develop science-based scenarios to support a strategy leading to a carbon-neutral Germany in 2050. ii) We also provide extremely detailed impact scenarios or projections to support the need for timely decision-making to create adequate measures. iii) We will develop coherent communication strategies and campaigns aiming to raise the awareness and to interact with society on the issue of climate change impacts, risks and challenges.

Relevance and Strategy. The Helmholtz Association hosts a tremendous breadth of excellent competencies, which can contribute to solution options related to this grand societal challenge, especially when networked across centers and RFs. HI-CAM, which is supported by the Initiative and Networking Fund of the Helmholtz President with 12 Mio. € for a period of two years could, if successful, provide a blueprint for how to better exploit synergies within Helmholtz together with its strategic partners.

After this initial phase of two years, with pilot projects for mitigation and adaptation, the successful cooperation will continue and become part of the long-term research of PoF IV. A key element of the HI-CAM strategy is to reach out to national and international science partners, involve major stakeholders as well as industry to provide a more coherent picture and a more attractive interface to the outside world, improving the overall impact and visibility of Helmholtz in the climate field and help overcome the usual institutional barriers within the science community.

Involved Partners. All centers in the RF E&E (with key connections to T1, T2, T3, T4, T5, T7, T8) and the RFs Energy, Health, Information, Matter and Aeronautics, Space and Transport.

Approaches, Methodologies, Measures. The **mitigation** part of HI-CAM aims to pave the way for possible routes to reach net-zero and thereby also to provide scientifically sound and transparent information on the

[19] See https://www.reklim.de/en/knowledge-transfer/.

potential of key technologies under different scenarios, as well as against the background of the specific economic and societal feasibility at first with a focus on national scale. At the same time, information about mitigation potentials in different sectors, CO_2 storage and utilization potentials in natural and artificial systems, and new technologies for CO_2-neutral systems are already available and will be compiled and assessed comprehensively. This will be carried out in close interaction with stakeholders to develop consistent scenarios for the required substantial changes at all levels of society in order to reach net-zero by 2050. In the **adaptation** part, the tremendous improvement in scientifically based process knowledge, the improvement in computing power and the availability of high-quality data from innovative sensors in space and on the ground will be used to develop robust Pictures-of-the-Future with an unprecedented richness and resolution. These scenarios will combine large-scale climate change projections and detailed multi-sectoral local impact modeling to develop possible courses of action in Germany and Europe. Special emphasis will be placed on extreme events and the identification of effective cross-sectoral adaptation measures. The third element is a specific **communication** package, where tangible Pictures-of-the-Future will be shared with the public, ranging from key societal representatives, stakeholders of the various economic sectors as well as decision-makers at European, national, but also at the local level to develop concrete options for actions. Special emphasis will be given to a direct and responsive dialogue with the interested public, specifically young people interested in climate science and climate politics.

Important Preliminary Work. HI-CAM draws from the expertise of 14 different Helmholtz centers in the RFs E&E, Energy, Health, and Aeronautics Space and Transport. More than 50 PIs are contributing and communicating within two well-structured project clusters under central coordination and an executive-level steering committee.

2.1.3 Resilient Urban Spaces

with RF Aeronautics, Space and Transport, RF Health, and RF Energy | Coordinators: Bernd Hansjürgens, UFZ; Fabrice Cotton, GFZ; HaPe Schmid, KIT

Running Time. A new initiative, starting with PoF IV in 2021.

Planned FTE (scientists) in PoF IV. No FTE allocated yet.

Challenges. Cities and urban areas are major drivers of global and climate change. As hot spots of population shifts (growth and shrinkage), economic development, land take, resource use, greenhouse gas emissions and transport, they are particularly vulnerable to hazards, disruptive natural events and environmental change. Extreme events and change processes affect urban areas within city boundaries, but also their relation to the hinterland and the urban-rural nexus with its food, water and energy connections. Research towards resilient and sustainable cities thus needs a joint effort of as yet, fragmented competences. The challenge is to identify urban inhabitants' exposure to and capacity to cope with, extreme events, to analyze environmental impacts on urban resilience and citizens' quality of life and to identify and propose pathways towards sustainable urban areas.

Objectives. The overall objective is to mitigate urban climate change risks and increase the adaptive capacities and resilience of urban areas. Based on extensive studies carried out e.g., in Leipzig, Istanbul, Dar es Salaam, and Santiago de Chile, specific objectives are the development of proposals that i) enable urban spaces to cope with multi-hazards and climate risks, ii) provide healthy environments for their inhabitants; and iii) develop novel technological and system solutions for infrastructure management. Resilient Urban Spaces will be organized in a modular setup:

- Hazards and urban risks (**GFZ**, KIT, GEOMAR, UFZ, HZG), focusing on time-dependent exposure (population, buildings, mobility networks, critical facilities) and vulnerability schemes that accommodate changes in the number and type of exposed assets to forecast the future impact of multi-hazards on cities.
- Healthy life in a smart city (**UFZ**, FZJ, GFZ, RF Health, HZG), focusing on the urban environment from an ecological and societal perspective, with urban green and blue infrastructures, novel societal adaptation strategies against climate extremes, and societal transformation processes to increase and maintain the livability of urban areas.

- Urban climate and environment (**KIT**, FZJ, UFZ): Urban climate and implications for air quality and quality of living. Observation and modeling of the urban fabric – atmosphere interactions from street-canyons to urban-rural circulation; emission of GHG, aerosol and air pollutant (precursors).

Relevance and Strategy. As nearly 60% of the world's population will live in urban areas by 2030, these spaces are decisive elements of the Earth system. Therefore the strategy is to build up a research network in PoF IV by combining research from T1 (urban climate and air quality), T3 (geo-hazards and time-dependent exposure), T4 (coastal zones), T5 (urban transformation pathways and resilience to extreme heat, droughts and floods), T7 (circular bioeconomy in the urban-rural nexus), T8 (minimizing induced seismicity of geothermal systems) and T9 (human and environmental health) and – stepwise – from the RFs Aeronautics, Space and Transport, Energy and Health. Based on conceptual and definitory works in a preparatory research phase, a coherent research network will be built up in the course of the Program to gain momentum on the national and international level.

Involved Partners. FZJ (T7, RF Energy), GEOMAR (T3), GFZ (T3, T8), HZG (T4), KIT (T1), UFZ (T5), DLR (RF Aeronautics, Space and Transport, RF Energy), HMGU (RF Health).

Important Preliminary Work. Urban Spaces is based on Helmholtz Research Initiative Risk Habitat Megacity; Center for Disaster Management and Risk Reduction Technology CEDIM; [UC]² (BMBF urban climate model and observation program); NAKO (German national cohort, GNC); MOP (mobility panel); TERENO (scale-integrating measurement strategies); GERICS Adaptation Toolkit for Cities; MATRIX (Multi-Hazard and Multi-Risk Assessment Methods for Europe).

2.1.4 Remote Sensing

with RF Aeronautics, Space and Transport | Coordinators: Martin Riese, FZJ; Jan Cermak, KIT; Jens Wickert, GFZ

Running Time. A new initiative, starting with PoF IV in 2021.

Planned FTE in PoF IV. No FTE allocated yet.

Objectives and Challenges. To strengthen the field of remote sensing within Helmholtz across Programs, and to advance the observation-based integrated analysis of the Earth-Atmosphere system, the Program will establish a collaboration with the RF Aeronautics, Space and Transport (DLR) in the field of remote sensing of the atmosphere and the Earth's surface by satellite-borne and airborne instruments, incl. the research aircraft HALO, as well as ground-based sensors.

Relevance and Strategy. The planned activities build on a long-standing strategic partnership of RF E&E and DLR and address the grand challenge of developing and enhancing observation systems at scales from local to regional and global scale. Common fields of specific interest are the characterization and monitoring of Earth system processes. Examples are ultra high-resolution land use and land use change as well as crop prediction assessments, photosynthesis studies, the mass balance of ice sheets in the polar regions, natural and anthropogenic hazards, impact delineation, space weather, atmospheric dynamics (e.g., gravity waves) and cloud processes. It is important to note that the RF E&E and DLR have collaboratively developed and positioned some large-scale research infrastructure on the national roadmap, all based on a long-standing successful scientific cooperation. At present this is the infrared limb imager AtmoSat coordinated by the RF E&E, TANDEM-L coordinated by DLR, and EnMAP, coordinated by DLR in cooperation with RF E&E. This is complemented by joint contributions to ESA's Earth Explorer missions.

Involved Partners. All centers in the RF E&E (with focus on T1, T2, T3, T5, T6, T7 and T8) as well as RF Aeronautics, Space and Transport (DLR).

Approaches, Methodologies, Measures. The partnership builds on atmospheric limb imaging methods providing unprecedented three-dimensional tomographic observations for AtmoSat and innovative lidar as well as optical (including hyperspectral), and synthetic aperture (SAR) techniques of unprecedented resolution and coverage for EnMAP and TANDEM-L.

Important Preliminary Work. Joint gravity-wave studies utilizing the infrared limb imager GLORIA (developed by FZJ and KIT) were made during the HALO campaign Gravity-Wave LCycle supported by a project within the BMBF-sponsored research focus ROMIC (Role of the Middle atmosphere in Climate). GLORIA will now be combined with highly innovative ALIMA lidar, currently developed at DLR, for the follow-on project SouthTRAC, also in the ROMIC framework. The hyperspectral observation technique has been significantly improved for monitoring Earth surface composition (e.g., soil and mineral resources, agricultural and natural ecosystems) in the EnMAP satellite program led by DLR in close collaboration with GFZ (launch early 2021). The synthetic aperture (SAR) technique has been improved significantly by DLR and the RF E&E to monitor dynamic processes on the Earth's surface (e.g., total biomass, soil moisture, processes in the cryosphere and geosphere). Using innovative data-handling and communication techniques, high-resolution images (<10 m) of the entire globe can be produced every 4.5 days.

2.1.5 Geoenergy

with RF Energy | Coordinator: Ernst Huenges, GFZ

Running Time. The activity started in 2013 and will run through PoF IV.

Planned FTE (scientists) in PoF IV. GFZ: 22; UFZ: 4; RF Energy: 12.

Objectives and Challenges. Up to 80% of the energy demand for urban and industrial areas is related to heating and cooling. The demand for heating and/or cooling fluctuates and changes seasonally. Excess in the summer can be stored in large volumes in the subsurface and provide base-load heat in the winter. 'Geoenergy' focuses on the deep underground as a source of and storage site for thermal energy. It includes storage in saline aquifers as well as heat recovery from greater depths for space heating, or even for process heat and power conversion. The collaboration will also combine subsurface use with the design of surface energy infrastructure and demand.

Relevance and Strategy. The energy system shift from fossil fuels to renewables requires robust, affordable solutions for energy storage on a large scale. The subsurface presents the largest, widely available storage space and allows the combination with geothermal energy provision, which is available as a base-load heat supply. The use of subsurface in the energy supply system requires multiple expertise, including materials and broad engineering, exploration and reservoir techniques. Case studies in industrialized areas such as the Campus North of KIT or combined heat/cooling systems in urban areas of Berlin or Hamburg will serve as demonstrators.

Involved Partners. GFZ and UFZ (T8), KIT (T4 of Program II, RF Energy).

Approaches, Methodologies, Measures. New exploration and subsurface monitoring approaches and tools will be developed and existing methods further refined to reduce the environmental risks and to better constrain geological processes controlling energy efficiency. Surface technologies will be further developed to supply and distribute the energy reliability and to integrate the supply of geoenergy into the energy provision system. For testing these approaches and technologies, large-scale research infrastructure representing reservoir conditions or deep underground research laboratories are required. It strives, therefore, to develop infrastructures to better constrain critical processes at full scale, to minimize the uncertainty of process parameters and to reduce the associated economic and environmental risks. The focus of the CARF Geoenergy as a research platform will include building public acceptance of the use of deep underground resources.

Important Preliminary Work. A long-standing collaboration of the partners in a joint PoF III Topic included detailed design studies for deep underground laboratories and high-temperature storage as well as the advancement of integrated exploration and monitoring approaches.

2.1.6 MACE: Mainstreaming Environmental Assessment for Complex Exposure

with RF Health | Coordinators: Rolf Altenburger, UFZ; Jörg Durner, HMGU; Michael Schloter, HMGU; Ulrich Schurr, FZJ

Running Time. A new initiative, starting with PoF IV in 2021.

Planned FTE (scientists) in PoF IV. No FTE allocated yet.

Relevance and Strategy. Environment and human health are closely linked. To see the full picture, this cooperation with the RF Health will i) define effects of global change impacts on ecosystems health and services, ii) define the effect these will have on humans (ONE health concept), iii) identify the effects on the European bio-based economy, and iv) support the mitigation of effects of future climate change on health and environment.

Identifying environmental factors that impact the epigenetic outcome or long-term adverse effects in organisms are of major concern since we realize that genetic causes are only a minor driver for adverse environmental and health outcomes. Several Program Topics address chemical exposure of biosystems in their specific contexts, such as combustion processes and air quality, diagnostic monitoring of multiple stressors, marine pollution and sustainable ecosystem use, or sustainable chemicals for future bioeconomy. To overcome a fragmented silo thinking, we will establish a platform to build coherent conceptual frameworks, cooperate in case studies, and coordinate generation of guidance documents.

Objectives and Challenges. The RF E&E requires novel and coherent strategies to assess hazards and risks for humans and Earth system compartments emerging from complex chemical and biotic exposures in the context of global change. For example, long-term biological adverse effects from chronic, low-dose exposure against multiple chemicals and non-chemical stressors pose major challenges for environmental assessment. These challenges comprise to translate human – in particular, children's – health research findings on causes of chronic disease into environmental quality measures. Moreover, we will synthesize environmental research outcomes to guide solution-oriented management of the environment.

Involved Partners. AWI (T6), FZJ (T1, T7), GEOMAR (T6), HZG (T4), KIT (T1), UFZ (T5, T7, T9), HMGU (RF Health).

Approaches, Methodologies, Measures. Communication, cooperation and coordination initiatives are planned within MACE. Dedicated initiatives are anticipated to establish conceptual frameworks for integrated assessments and stakeholder participation and to foster science interaction on joint approaches such as for microbiome studies. Case studies will be elaborated for themes such as particulate matter assessments, microplastic fate and effects in surface waters, plant stress response and food security, children cohort studies and the role of the exposome in environmental assessment. Established joint infrastructures (e.g., German Plant Phenotyping Network (DPPN) with hubs in FZJ and HMGU) will be used synergistically at the national level (DPPN) and in the European ESFRI-context (EMPHASIS). Coordinated actions will synthesize findings and tool evaluation for future resource management and advance sustainable chemistry within an emerging bioeconomy.

Important Preliminary Work. We build on established collaborative efforts, e.g., joint research activities between FZJ, KIT and HMGU on aerosols and human health, children environment cohort studies carried out between UFZ and HMGU. HMGU and FZJ have formed the Helmholtz Partnership for Plant Sciences (HP-PS), with joint governance between the participating institutes working on plant performance and health.

2.1.7 JL-ExaESM: Exascale Earth System Modeling

with RF Information and RF Aeronautics, Space and Transport | Coordinators: Martin Schultz, FZJ; Thomas Jung, AWI

Running Time. A new initiative, starting with PoF IV in 2021.

Planned FTE (scientists) in PoF IV. No FTE allocated yet.

Objectives and Challenges. Earth system modeling has significantly progressed over recent years. However, the field would still benefit from full compatibility with modern information science and technology paradigms. Modern supercomputing architectures are rapidly developing and getting increasingly complex because of physical and energy limitations to chip and storage system design. Making efficient use of next-generation HPC systems requires fundamental changes in software paradigms and workflows in numerical model and data analysis applications. JL-ExaESM will bring together leading groups from the RFs Key Technologies/Information, E&E, and Aeronautics, Space and Transport to explore novel IT hardware and software concepts for modeling and to enable future integrated high-resolution simulations on exascale computing systems. Specific objectives are: i) to develop new software paradigms to overcome the limited scalability (i.e., limitation in using a large number of compute cores) of existing ESM software on HPC platforms, ii) to increase the flexibility and portability of ESM software and workflows without compromising computational efficiency, iii) to explore novel concepts for improving the transport of huge amounts of information on hierarchical and federated storage systems, iv) to better understand the computational and data demands of future ESM codes for optimizing the design of exascale HPC architectures, v) to explore the use of machine learning to optimize or replace numerically expensive parameterizations in Earth system model components.

Relevance and Strategy. Existing models still have limitations in simulating extreme natural phenomena; and it has been argued that increases in resolution may provide major advances. Exascale computing provides the opportunity to push the boundaries of resolution. However, at the same time, exascale systems are far too complicated to be used in existing systems. JL-ExaESM lays a foundation to become an international leader in this rapidly emerging research area of high strategic relevance. It will allow taking a leading role in the national Earth System Modeling strategy in Germany and the European ExtremeEarth initiative, given that exascale-readiness plays a critical role in both. By adopting the co-design principle, the JL-ExaESM results will also influence Germany's and Europe's future development of exascale HPC architectures. Finally, JL-ExaESM will provide an important bridging function between the Helmholtz ESM project and the ESM partition at Jülich Supercomputing Centre.

Involved Partners. AWI (T1, T2, T4, T6), GEOMAR (T2, T6), HZG (T1, T4), UFZ (T5, T8), RF Information (Program 'Engineering Digital Futures: Supercomputing, Data Management and Information Security for Knowledge and Action'), RF Aeronautics, Space and Transport (Program 'Space').

Approaches, Methodologies, Measures. JL-ExaESM addresses questions of vital importance to generate a step-change in our ability to do Earth system modeling on next-generation, exascale high-performance computing systems and to enable geoscientists to handle and analyze associated big data. The project will explore novel software concepts (e.g., model dwarfs, asynchronous scheduling), address emerging IT issues (e.g., hierarchical data storage and interactive supercomputing), and it will utilize machine learning in modeling. The partnership will allow exploiting novel information and data science methods and tools to lay the foundation for next-generation Earth system models.

Important Preliminary Work. The JL-ExaESM builds on the recently awarded Incubator project Pilot Lab ExaESM, which will initiate the novel collaboration among scientists with expertise in computer science, modeling and simulation, data analytics, and Earth System Sciences. The partners have a long experience in running Earth system models, in manual execution of large-scale workflows on distributed computers, and in operating world-class HPC facilities.

2.1.8 BmE: Bioeconomy meets Energy

with RF Energy | Coordinator: Uli Schurr, FZJ

Running Time. The activity started in 2005 and will run through PoF IV.

Planned FTE (scientists) in PoF IV. FZJ: 4.5; UFZ: 3; RF Energy: 4.5.

Objectives and Challenges. Biomass will have an important role in a future circular economy as a source of materials and energy. The sustainable and economically viable utilization of biomass will be integrated into a bioeconomy approach developed jointly by the two RFs. We will study novel processes, process chains and products using hybrid approaches by combining, e.g., biochemical, (bio)electrochemical, chemo-catalytic, electro-catalytic, thermo- and photochemical processes. Specific objectives are to provide spatial explicit renewable energy, chemistry and biomass options and assessments including i) life-cycle based assessment of ecological, economic and social sustainability aspects and ii) the analysis of trade-offs and conflicting targets from a systemic view.

Relevance and Strategy. Circular economy approaches in the RF Energy Program Materials and Processes for the Energy Transition (MTET) require our collaboration to produce feedstock sustainably and to optimize quality specifically to the diverse utilization and conversion pathways. We will jointly optimize, e.g., perennial crops, algal strains and their production systems, and develop dedicated processes for their pretreatment and conversion. Optimizing cyclic nutrient flows integrating feedstock, biorefineries and recycling of nutrients into feedstock production is also a unique opportunity. Syngas fermentation at KIT will be extended by a carboxylate platform established at UFZ. Thermochemical conversion of biomass will be interlinked with fermentation processes in the RF E&E. Information will be linked to energy system analysis including wind, solar and biomass and the expectation on biofuels for different applications.

Involved Partners. UFZ (T5, T7), FZJ (T7 and RF Energy, Programs 'Energy System Design', ESD, and MTET), KIT (RF Energy, Programs MTET and ESD).

Approaches, Methodologies, Measures. The cooperation will include joint experiments exchanging alternative feedstock and biorefinery residues. Biorefinery options using different conversion routes will be developed and evaluated. Bioeconomy scenarios and integration into a hybrid cyclic economy will be jointly developed and evaluated for technical and economic feasibility and environmental impact.

Important Preliminary Work. We build on established collaborative efforts through PoF III and long-term interaction towards the wider bioeconomy research landscape within Helmholtz, at national and international levels.

2.1.9 Nuclear Repository Research

with RF Energy | Coordinators: Michael Kühn, GFZ; Olaf Kolditz, UFZ

Running Time. A new initiative, starting with PoF IV in 2021.

Planned FTE (scientists) in PoF IV. No FTE allocated yet.

Obectives and Challenges. The aim is to provide a holistic scientific view on the safety of nuclear repository systems and to quantify their close-to-reality evolution with regard to physical, chemical and microbiological processes. Specific objectives comprise the development of experimental and modeling capabilities for up-scaling related multi-physical and biogeochemical processes from lab to field scales and establishing seamless workflows for safety/performance analysis/assessment including data science methods, respectively.

Relevance and Strategy. The safe, reliable disposal of Germany's nuclear waste requires a long-term perspective on the processes that control the integrity of potential host rocks. The cross-scale research concept of this CARF will provide a considerably enhanced scientific basis for an in-depth comparison of different repository concepts as specifically required for the site selection procedure in Germany. The long-term vision of the project is to establish a multidisciplinary scientific Helmholtz research competence center offering a nuclear waste disposal research platform with high international visibility and impact, being attractive to young scientists and cooperating with relevant research institutions and authorities.

Involved Partners. GFZ (T3, T8), UFZ (T8), KIT, FZJ, HZDR (RF Energy, Program 'Nuclear Waste Management, Safety, and Radiation Research', NUSAFE).

Approaches, Methodologies, Measures. The cross-scale research concept will combine the understanding of the Earth system by applying geoscientific expertise and unique environmental simulation capabilities (RF E&E) with analyses of radioactive waste from and radionuclide behavior in repository systems by applying unique research infrastructure (RF Energy). A notable feature will be the integration of data from in situ (e.g., Underground Research Laboratories like Mont Terri) and laboratory experiments into reactive transport models, where thermo-hydro-mechanical-chemical-biological processes in repository systems can be analyzed, enhancing the comprehension of coupled processes across scales.

Important Preliminary Work. This activity is based on the iCROSS project ('Integrity of nuclear waste repository systems – Cross-scale system understanding and analysis') funded by the Initiative and Networking Fund of the Helmholtz President and the BMBF.

2.1.10 ARCHES: Autonomous Robotic Networks to Help Modern Societies

with RF Energy and RF Aeronautics, Space and Transport | Coordinators: Armin Wedler, DLR; Frank Wenzhöfer, AWI; Stefan Sommer, GEOMAR

Running Time. 2018–2020, shall be continued in PoF IV.

FTE (scientists) from 2018 to 2020. AWI: 3; GEOMAR: 3; RF Aeronautics, Space and Transport: 6; shall be continued in PoF IV.

Objectives and Challenges. The aim of the Helmholtz Future Project ARCHES is the development of heterogeneous, autonomous and interconnected robotic systems in a consortium of the Helmholtz centers DLR, AWI, GEOMAR and KIT (2018 to 2020). The future fields of application span from the environmental monitoring of the oceans over technical crisis intervention to the exploration of the solar system. Objectives are to develop approaches that allow robots to acquire, analyze, and interpret measured data autonomously. Consequently, the scope of ARCHES also includes the intelligent automation and cooperation of robotic systems. Both of these aspects are essential considering the importance of standalone robots and robot teams in both regarded applications and domains: deep sea and space. The project aims to develop common solutions for the challenges mentioned earlier and will establish cross-domain interfaces. The aim in ARCHES and for PoF IV is further to develop and deploy long-term ocean observatory networks that record and fuse data from the atmosphere through the sea ice and water column, and ultimately to the seafloor. The scientific goal is to determine major drivers and causal relationships of physical forcings, faunal distribution and biogeochemical processes.

Relevance and Strategy. The importance of robotics for industry and science is continuously growing. In the long run, robotic systems will become indispensable for modern societies as an omnipresent and tireless workpower resource and autonomous robot networks will become a key technology.

In particular, solving tasks like monitoring and understanding the ocean environment or exploration of the solar system will strongly depend on the deployment of autonomous and networked robotic systems. They will provide the required capabilities for continuous, long-term, and large-scale data recording as well as for manipulation and direct interaction with the surroundings. Robots allow monitoring and object manipulation on a large scale in harsh and vast environments. Accordingly, a robot network will be created within this project, which acts as an enhancement of human perception and as an extended arm for human manipulation.

Involved Partners. AWI (T6), GEOMAR (T2), KIT (RF Energy, Programs NUSAFE & 'Autonomous Systems'), Coordinator: DLR (RF Aeronautics, Space and Transport, Program 'Space').

Approaches, Methodologies, Measures. Networks of robotic systems will be developed that fulfill the requirements for robustness and reliability characteristic for the domains. The existing hardware platforms consisting of configurable carrier systems as well as modules of sensors and manipulators that are interchangeable for applications in different systems and domains will be cross-validated. That way, the goal of creating synergies within the network of expertise will be realized.

On the way to fully understand natural variability as well as the impact of human activities on the oceans and their consequences for the marine ecosystem, and the system 'Earth' as a whole, humanity faces substantial challenges. To resolve the linkages and to distinguish between anthropogenic and natural causes as well as to account for a highly variable system in space and time, cooperating networks of robotic and synchronized autonomous multiple sensor systems are needed.

Further applications in other fields like medicine, rehabilitation, logistics and urban transportation will benefit from the fundamental concepts developed in ARCHES.

Important Preliminary Work. ARCHES builds on the successful Helmholtz Alliance 'Robotic Exploration of Extreme Environments – ROBEX' (2012–2017). ROBEX brought together the world's first integrated space and deep-sea research group. Sixteen institutions from all over Germany jointly developed technologies to improve the exploration of extreme environments such as the deep sea, polar regions, the moon and other celestial bodies. These technologies were successfully demonstrated during two 'Demonstration Missions' (for the marine science on Polarstern near Spitsbergen and the space science as Moon-Analogue Mission on Mount Etna).

2.2 Cross-Topic Activities (CTAs)

2.2.1 MOSES: Modular Observation Solutions for Earth Systems

Coordinator: Ute Weber, RF E&E with contract at UFZ

Running Time. Implementation phase 2017–2021; regular operation starts in 2022.

Planned FTE (scientists) in PoF IV. AWI: 2; FZJ: 2; GEOMAR: 1; GFZ: 2.5; HZG: 3; KIT: 4; UFZ: 9.

Objectives and Challenges. MOSES is a new observing system developed by the RF E&E. It comprises highly flexible and mobile observation modules which are specifically designed to unravel the impact of short-term events on the long-term development of Earth and environmental systems. Highly dynamic events such as heatwaves and droughts, hydrologic extremes, abrupt permafrost thaw and ocean eddies are in the focus of this event-oriented observation and research initiative. The main objective is to capture events from their origin to their fading with high-resolution observations. The investigation of such events is most acute as the impact of global and climate change becomes increasingly evident. As such, MOSES complements and extends existing national and international monitoring networks like TERENO, ICOS or eLTER, which are primarily designed for long-term Earth observation.

Relevance and Strategy. Although it is well known that the Global Change affects the Earth and environment at many different time and length scales, currently, only very limited knowledge is available on the importance of such distinct dynamic events for the long-term development of Earth and environmental systems. With this joint facility, the participating centers integrate their wide-ranging scientific and technical expertise to close this knowledge gap. MOSES' event-oriented observation campaigns will be operated, and the resulting data sets processed in close cooperation with the Topics and Cross-Topic Activities of the RF E&E to improve understanding and predictions of climate and environmental change.

Involved Partners. AWI (T4, T5), FZJ (T1, T7), GEOMAR (T2, T6), GFZ (T3, T5), HZG (T4, T5), KIT (T1), UFZ (T4, T5), DLR (RF Aeronautics, Space and Transport), HMGU (RF Health).

Approaches, Methodologies, Measures. Enabled by a 30 Mio. € Helmholtz infrastructure investment, MOSES is designed as a 'system of systems' with significant scientific and technical personnel resources committed by the participating centers. During the implementation phase from 2017 to 2021, the centers develop, miniaturize and automate sensor systems, which are combined into specific observation modules. These record energy, water, greenhouse gas and nutrient cycles on the land surface, in coastal regions, in the ocean and the atmosphere – but especially the interactions between Earth compartments. The regular operation starts in 2022.

Important Preliminary Work. MOSES builds upon the comprehensive knowledge and experience of the RF E&E in developing and managing Earth observation infrastructure. First test campaigns started in 2018 at TERENO and COSYNA sites to train and optimize event-driven operations. These test campaigns will be continued until 2021 with increasing observational complexity and at different national and international sites like the Cape Verde Ocean Observatory (CVOO) and the Samoylov Permafrost Observation Station in Siberia.

2.2.2 TERENO: Terrestrial Environmental Observatories

Coordinator: Harry Vereecken, FZJ

Running Time. The activity started in 2008 and is planned to run through PoF IV.

Planned FTE (scientists) in PoF IV. FZJ: 7; GFZ: 2; KIT: 9; UFZ: 10.

Objectives and Challenges. The objective of TERENO is to assess the impact of climate change on the terrestrial system (from atmosphere down to groundwater) through integrated observation, novel methodologies and integrated model development. It contributes to the definition of climate adaptation strategies and the objectives 1, 2, 5, 7, 8 and 9 of the Program 'Changing Earth.'

Relevance and Strategy. TERENO is a key platform in Helmholtz for the assessment of climate impact on terrestrial systems in Germany, contributing to T1, T5, T7 (coordinating), and T9. The data from the observatories are made publicly available and are accessible online through the data-portal TEODOOR. Combining long-term observations and integrated models is essential to develop medium and long-term adaptation strategies for the management of agricultural and forest systems under climate change (T1, T5, T7), for the assessment of the impact of climate change and land-use change on biodiversity and human health (T5, T9) and the sustainable use of natural resources such as soils and water (T5, T7, T9). TERENO is an essential platform for operating MOSES in Germany.

Involved Partners. FZJ (T1, T7), GFZ (T2, T5), KIT (T1), UFZ (T5, T7, T9) and DLR (T1).

Approaches, Methodologies, Measures. TERENO consists of four terrestrial observatories that represent typical landscapes in Germany and Central Europe, which are considered to be highly vulnerable to the effects of global and climate change. TERENO combines observations with comprehensive large-scale experiments, integrated modeling and remote sensing as well as novel measurement technologies to increase our understanding of the functioning of terrestrial systems and the complex interactions and feedback mechanisms between their different compartments. Several of the TERENO observatories host large-scale infrastructures such as ICOS and the CZOs (Critical Zone Observatories). The extension of the TERENO integrated observatory concepts to European scale will be achieved through the recently approved ESFRI infrastructure project eLTER for which TERENO served as a blueprint.

Important Preliminary Work. TERENO has been in operation since 2008 and will be continued in PoF IV.

2.2.3 ESM: Advanced Earth System Modeling Capacity

Coordinator: Thomas Jung, AWI

Running Time. 2017–2021, shall be continued in PoF IV.

Planned FTE (scientists) in PoF IV. AWI: 4.5; FZJ: 4.5; GEOMAR: 4.5; GFZ: 4.5; HZG: 4; KIT: 5; UFZ: 6; DLR (RF Aeronautics, Space and Transport): 4.5.

Objectives and Challenges. Human society is facing a growing number of challenges, such as mitigation and adaptation to climate change and extremes, securing food production for a growing population and sustaining ecosystem services and the provision of bio- and georesources. We thus need to develop tools that provide decision-makers with the information required to effectively manage the opportunities and risks that come with these changes. Modeling is such a tool, as it enables investigating problems in an integrated manner including interactions between different Earth system compartments and across scales – from local to global scales, and from short weather to millennia and longer time scales. The overall objective of ESM is to develop and apply innovative Earth system modeling capacity that enables the scientific community to contribute to solving some of the grand challenges humanity is facing. More specific scientific objectives include i) improvements in the representation of key processes in models, ii) establishment of a coordinated approach towards coupling Earth system model compartments, and include new compartments, iii) development of common data assimilation capacity, and iv) coordination of simulations in support of the whole Program (so-called 'frontier simulations'). A strategic objective is the development of a long-term modeling strategy, including harmonization of modeling activities within Helmholtz.

Relevance and Strategy. Modeling allows the addition of a strong outcome-related component to the Program by facilitating predictions and projections. Models can also be used to explore options and advance research, for example by supporting effective monitoring (Smart Monitoring in CTA Digital Earth) and by providing guidance for the design of observing systems and in support of targeted field campaigns (e.g., CTA MOSES). ESM will enable a step-change in our modeling capabilities. It will be doing so through increased investments in modeling, by exploiting synergies between the different centers and by sharing important modeling infrastructures. ESM is the first out of three pillars of Helmholtz to strengthen the field of modeling, the second and third being the dedicated Earth system modeling partition at Jülich Supercomputing Centers, and CARF JL-ExaESM, respectively. ESM will also be the platform for strategic discussions with other modeling groups at the national and international level.

Involved Partners. AWI (T1, T2, T4, T6); FZJ (T1, T7); GEOMAR (T2, T6); GFZ (T2, T3, T8); HZG (T1, T4); KIT (T1); UFZ (T5, T8); DLR (RF Aeronautics, Space and Transport).

Approaches, Methodologies, Measures. In ESM, we improve the representation of key processes in Earth system model compartments for which the partners have proven expertise. We also develop, test and apply frameworks that can be used for efficiently bringing different model components together (e.g., ESM-Tools). Furthermore, we will develop and use a common data assimilation framework (e.g., employing the Parallel Data Assimilation Framework, PDAF) to effectively combine models and observations. Moreover, partners will carry out coordinated frontier simulations that will be made available to the scientists in the different Topics for pushing the boundaries of existing knowledge. Finally, ESM will also provide the framework for the strategic development of modeling activities in Helmholtz involving critical external partners (e.g., Max Planck Institute for Meteorology, DWD, and the Geo.X hub[20]).

[20] See https://www.geo-x.net.

Important Preliminary Work. Strong expertise is available in the modeling of Earth system compartments from the deep geosphere to the upper atmosphere. Partners have also demonstrated crucial expertise in bringing together different components in Earth system models. Furthermore, expertise is available in the development and application of advanced data assimilation approaches. All partners have a track record in running models on high-performance computing systems and collaborate closely with HPC centers.

2.2.4 DE: Digital Earth – Towards Smart Monitoring and Integrated Data Exploration of the Earth System

Coordinator: Jens Greinert, GEOMAR

Running Time. 2017–2021, shall be continued in PoF IV.

Planned FTE in PoF IV. AWI: 0.5; FZJ: 1.5; GEOMAR: 3.5; GFZ: 3.5; HZG: 2.5; KIT: 4; UFZ: 4.

Objectives and Challenges. The objectives of Digital Earth (DE) are threefold, i) to guide data acquisition through better and faster analyses of field and model data including predictions in space and time (Smart Monitoring), ii) to advance capabilities and competences with respect to visual and computational data analyses and synthesis (Data Exploration), and iii) to establish structures for sustainable collaboration among the centers and external experts in data science to spread knowledge, reduce redundancies and enable sustainable development in data science. Challenges within DE are given through the large amount of data from the different Earth compartments, their different temporal and spatial resolution, data formats as well as data volume.

Relevance and Strategy. Rapid growth in the amount of data and computing power, as well as enhanced analytical methods, now enable a data-driven approach to be included in the scientific workflow of knowledge generation. Together with the current focus on 'digitalization' not only in society but also in science, makes a CTA with a data-driven approach essential and timely for our future progress in Earth system understanding and predictability. DE will help to exploit synergies through better coordination of ongoing data science activities and sharing of important infrastructure. In addition, the data-driven approach of DE to explore and analyze the Earth system is complementary to the modeling approach in ESM.

Involved Partners. AWI (T2), FZJ (T1 and T7), GEOMAR (T1, T2, T3, T6, T8), GFZ (T2, T3, T5), HZG (T5), KIT (T1), UFZ (T5), HMGU (RF Health).

Approaches, Methodologies, Measures. Digital Earth adapts and tests data analysis methods, including machine learning and visual analytics to explore and analyze multivariate and high-dimensional data sets from observations and models. It also implements digital scientific workflows for combining and exploring data from various sources to improve and fasten the scientific working process and also to guide data acquisition by the Smart Monitoring concept. DE develops a component-based Data Exploration Framework to integrate and combine data processing and analysis methods for a variety of scientific tasks. DE provides the framework for the strategic development of data science activities in the RF E&E, also involving important external partners. To foster collaboration, several center-overarching discussion groups are already established within the CTA DE. Themes of these groups are Earth Monitoring, Data Flow, Data Exploration (visual and computational), Data Management & Governance and Software Architecture Concepts. Digital Earth is closely linked to the CTAs MOSES, TERENO and ESM, the CARF JL-ExaESM as well as the Alliances DAM and DESA.

Important Preliminary Work. The CTA DE already set up a communication concept, established a management layer across all centers to exchange information and closely links to other initiatives within the Helmholtz Association as the Incubator Projects HAICU, HIP or HIDA. The computational aspect is also part of the Helmholtz School for Marine Data Science (MarDATA), which is hosted at GEOMAR in cooperation with AWI.

2.2.5 Extremes: Extreme Events in a Changing World

Coordinators: Ute Hentschel-Humeida, GEOMAR; HaPe Schmid, KIT; Fabrice Cotton, GFZ

Running Time. A new initiative, starting with PoF IV in 2021.

Planned FTE (scientists) in PoF IV. No FTE allocated yet.

Objectives and Challenges. Extreme events related to atmospheric, geospheric, geological or oceanic disturbances pose a potential threat to societies, their assets and the environment. Given the statistical properties of extreme value distributions, weather and climate extremes are expected to increase disproportionately in the future, along with further upward shifts, e.g., in mean temperature, ocean acidification, or oxygen deficiency. Moreover, societies are becoming increasingly vulnerable as a result of growing globalization and urbanization, the increasing dependence and degree of penetration of critical infrastructures, and the concentration of assets in hazard-exposed regions.

The impact of extremes can even be substantially aggravated depending on the temporal sequence of the events such as i) hazards occurring simultaneously ('compound events'), ii) events that trigger subsequent events ('cascading effects'), and iii) series of hazardous events affecting the same region (days to weeks; 'serial clustering'). Although these different types of multi-hazards can have a damage potential that goes far beyond what has been experienced so far, they have only been examined marginally, and their drivers are poorly understood. In the context of environmental changes and marine life it is largely unknown how species and communities react, are resilient to, and may recover from, e.g., sea surface temperature extremes, related mass coral bleaching and macroalgae die-offs.

Within a multi-hazard and holistic risk framework T1 focuses on heatwaves, storms and hail, T2 on climate extremes and remote drivers, T3 on geo-hazards (earthquake, volcanic eruptions, tsunami, landslides), T4 on coastal cities at risk, T5 on riverine flooding and droughts, T6, on marine hazards, T7 addresses aspects of extreme weather in relation to crops and crop management, and T9 examines altered exposure patterns resulting from flooding.

Involved Partners. AWI (T2), FZJ (T7), GEOMAR (T2, T6), GFZ (T2, T3), HZG (T4), KIT (T1), UFZ (T5, T9).

Approaches, Methodologies, Measures. New concepts for modeling the dynamics of multi-hazard events will be addressed, making use of large data archives available in all Topics, including open- and crowd-sourced data, combined with high-resolution climate modeling.

Important Preliminary Work. KIT and GFZ have developed several single- and multi-hazard and risk approaches (e.g., Risk Explorer and Forensic Disaster Analysis in the Center for Disaster Management and Risk Reduction Technology, CEDIM) and risk models (windstorm, hail, floods, earthquake), operationally applied in the insurance industry, and EU FP7 supported project MATRIX (Multi-Hazard and Multi-Risk Assessment Methods for Europe).

2.3 Alliances

2.3.1 DAM: Deutsche Allianz für Meeresforschung – German Alliance of Marine Research

Coordinators: Peter Herzig, GEOMAR; Karsten Wurr, AWI

Running Time. A new initiative, founded in 2019.

Planned FTE (scientists) in PoF IV. No FTE allocated yet.

Objectives and Challenges. The marine research institutions in Germany (including the Helmholtz Association, the Leibniz Association, the Max Planck Society, and universities) founded the German Marine Research Alliance e.V. (DAM) in July 2019. DAM will integrate marine expertise, infrastructure and data management with the objective to tackle large societal relevant questions for protection and sustainable use of the ocean and seas. In the context of DAM, all fields of marine, coastal and polar science are considered. DAM has four main areas of operation to improve synergies among national marine research groups in all disciplines: research missions, data management, infrastructure and knowledge transfer.

Relevance and Strategy. The Program 'Changing Earth' has a key role in all aforementioned DAM areas. The integrated approaches to marine research that are required to understand and address challenges in marine systems demand the alignment of all expertise available in marine research. The DAM research missions will bring related information from all partner institutions into an overarching consideration and thus enhance the scope of the Program. Strategies for common use, financing and operation of marine infrastructures will be developed within DAM. Transfer of knowledge, links to stakeholders and capacity building in DAM will focus on the themes of the research missions and supplement the activities of the member institutions, including additional funding.

Involved Partners. AWI, GEOMAR, HZG, Center for Earth System Research & Sustainability, University Hamburg; Department Maritime Systems, University Rostock; Institute for Chemistry and Biology of the Marine Environment, University Oldenburg; Kiel Marine Science, University Kiel; Leibniz Institute for Baltic Sea Research Warnemünde; Leibniz Center for Tropical Marine Research; MARUM Research Faculty University Bremen; Max Planck Institute for Marine Microbiology; Max Planck Institute for Meteorology; Senckenberg Research Institute Wilhelmshaven.

Approaches, Methodologies, Measures. The Program 'Changing Earth' links to DAM research missions specifically via T2, T4, T6 and T8. DAM will support the digital transformation of marine science and as a first step develop a common infrastructure for open, sustainable access to marine research data (ship data and marine observatories). AWI, GEOMAR and HZG provide the majority of the sea-going infrastructures for marine and polar research and will develop a joint concept for the optimization of use together with its partners. The transfer activities of the Program will be brought together with those of the other members of the Alliance targeted for the specific themes of the DAM research missions.

Important Preliminary Work. The preliminary work was undertaken based on the agreement of the five North German Federal States (Bremen, Hamburg, Lower Saxony, Mecklenburg-Vorpommern, Schleswig-Holstein) and the BMBF to support the Alliance ideally and financially. It is anchored in the present Coalition Agreement of the German Government.

2.3.2 DESA: Deutsche ErdSystem Allianz – German Earth System Alliance

Coordinator: Reinhard Hüttl, GFZ

Running Time. A new initiative, starting with PoF IV in 2021.

Planned FTE (scientists) in PoF IV. No FTE allocated yet.

Objectives and Challenges. DESA aims to be a nucleus for the integrated Earth System Research across Germany by bundling existing expertise, tackling present and future infrastructure challenges, and fulfilling the task of science, and knowledge and technology transfer. This addresses all compartments of the Earth system.

Relevance and Strategy. In DESA, research and development in the field of Earth system analysis are bundled across institutions to jointly meet the challenges of a globally networked society in dealing with significant changes in the environment. The complexity of Earth System Science requires alignment and cooperation across all available expertise in Germany and (mid-term) in Europe. Therefore, the RF E&E initiated DESA with its partners from other relevant research organizations, centers and institutes in Germany.

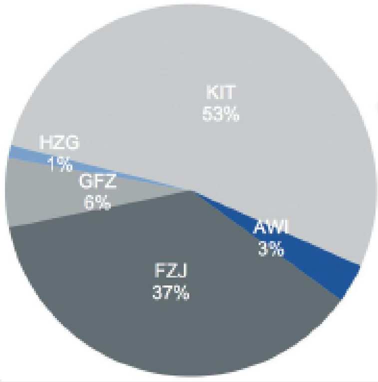
Involved Partners. Beside the Helmholtz centers of the RF E&E, DESA shall include university institutes, research institutes of the Leibniz Association and the Max Planck Society as well as federal institutes and state services. This can build on the initially Helmholtz-funded Geo.X network of the Berlin/Potsdam region that has started a strategic partnership of Helmholtz, Universities, and Leibniz. It develops novel research approaches and training concepts at the interface of scientific disciplines, and coordinates regional community building activities in NFDI4Earth.[21]

Approaches, Methodologies, Measures. DESA members will contribute their existing research infrastructures as well as platforms for exchange and joint development in the field of knowledge and technology transfer with interfaces to business, politics and the public (SynCom). This includes i) the synthesis of knowledge in ad-hoc actions and medium-term working groups, in conjunction with ii) the development of common communication and mediation strategies, iii) the coordination of the joint construction and operation of large-scale facilities and research infrastructure, e.g., the expansion and construction of observatories for inter- and transdisciplinary Earth system analysis, and iv) a joint concept in the field of research data management. With an additional Helmholtz start-up funding and after a test and implementation phase, DESA could be in place for the start of PoF IV in 2021.

[21] See https://www.nfdi4earth.de.

Topic 1: The Atmosphere in Global Change

Spokespersons: HaPe Schmid, KIT; Johannes Orphal, KIT



Topic 1 addresses three research areas of societal relevance for the Atmosphere in Global Change: Air Quality, Climate Feedbacks, and Future Weather and Extremes. Knowledge in these areas provides guidance to assess adaptation and mitigation measures as we approach the 1.5°C global warming limit. We will develop observational and modeling solutions for improved atmospheric predictions and regional climate projections at unprecedented resolution, in a **'whole atmosphere' approach**, to address entire process- and event chains from the drivers of global change or extreme events to their ramifications for air quality, water resources, greenhouse gas budgets, land use change, ecosystem viability, and the risk of more extreme weather in a warmer world. As part of our international benchmarking strategy, we foster open exchange and collaboration with the best atmospheric and climate research teams globally.

A) Scope and challenge of the Topic

Research subject. The atmosphere is Earth's thin protective layer that shields us from harmful radiation, moderates temperature differences and redistributes energy, water, and pollutants: most life depends on it. But this protective function of the atmosphere involves delicate balances and is susceptible to global change of climate and land use. The primary drivers of climate change are the radiative effects of greenhouse gases (GHG) and of aerosols, which affect the composition and inner workings of the atmosphere, and all adjacent Earth system compartments. The strongest global climate mitigation effect is achieved by land ecosystems, but through feedback mechanisms, they are themselves vulnerable to climate change, and land use change also causes emissions. Topic 1 (T1) contributes to seamless observational and modeling capabilities to unravel the complex interactions between the atmosphere, the land surface, and the ocean under climate change. The focal themes are 'Air Quality', 'Climate Feedbacks', and 'Future Weather and Extremes'. Progress in these areas is of topmost relevance for reliably assessing the state of the Earth system, and for predicting and projecting global change impacts on our future living conditions.

Explanation and justification of research. Climate- and weather-related environmental risks (i.e., extreme weather events, natural disasters, and failure of climate change mitigation and adaptation) rank in the top four global risks to society (by likelihood and worldwide impact; GRRT 2019).[16] Urgent action for climate mitigation and adaptation is necessary within the next decade to prevent global mean temperatures from rising beyond the Paris Agreement's 1.5°C global warming limit (UNFCCC 2015).[17] Within this setting, T1 will develop better observational systems and new regionally explicit knowledge to assess the effectiveness of mitigation, and potential consequences of adaptation measures.

[16] World Economic Forum Davos 2019. 14th Global Risk Report.

[17] UNFCCC 2015. The Paris Agreement.

Our research follows a **'whole atmosphere' approach:** we aim at developing scale-crossing observational and modeling solutions for improved atmospheric predictions and regional climate projections at unprecedented resolution. We strive to observe, understand and predict atmospheric phenomena and process chains from drivers to climate change impacts throughout all levels of the atmosphere, and especially in their interaction and feedbacks with the adjacent compartments, i.e., land surface, biosphere, cryosphere, ocean, and near-Earth space. T1 assesses the physical, chemical, and socio-ecological consequences of atmospheric change and its ramifications for climate, extreme weather, and land ecosystem functioning. By this integrative 'whole atmosphere' approach, T1 will substantially improve the scientific knowledge base for responding to societal challenges such as global warming, growing world population, land use change, air quality improvement, water availability, and transformation of energy- and mobility systems. T1's atmosphere- and climate-related observational and modeling activities will establish the scientific basis of sustainable development strategies for the benefit of society, ecosystems, and climate mitigation and adaptation, in conjunction with economic risk reduction.

T1 benefits from, and largely builds on, **research expertise and experience** established in the previous **Helmholtz Program 'Atmosphere and Climate' (ATMO).** In PoF IV, new working groups that focus on the interaction of the atmosphere with the adjacent compartments land surface, biosphere, cryosphere, ocean, and near-Earth space will contribute to the integral 'whole atmosphere' approach.

Strategic guidelines (FoPoZ). The key-terms in the FoPoZ with the most relevance for T1 include: holistic view of the entire system, urban spaces, climate change, extremes, air quality, and research infrastructure. In close accordance with the FoPoZ,[18] T1 directs its principal research effort at regional spatial and sub-seasonal to seasonal temporal scales, which are particularly relevant for decision-making processes in questions of water resources, agriculture, air quality and natural hazard management (storms, floods, droughts, heat waves; particularly in urbanized regions).

Primary focal areas of T1 research are climate-sensitive regions in Europe, South-East Asia, and Sub-Saharan Africa (building on long-standing research collaborations in both West-Africa and East-Africa), as well as mesosphere-climate interactions.[19] Our African activities strongly contribute to the implementation of the 'BMBF Africa Strategy'[20] and are staged with on-going BMBF-funded projects in the framework program FONA.[21,22]

We will press forward on our proven path of innovation and expertise in scale-crossing observational and modeling work for **improved atmospheric predictions and regional climate projections at unprecedented resolution.**[23] Such high-resolution information is needed to design adaptation measures for, e.g., secure water availability, air quality, and food production. New observation techniques at high temporal and spatial resolution will be invaluable tools to calibrate and evaluate models, and thus serve to improve predictive skill for extreme weather, and of probabilistic forecasts of weather systems at sub-seasonal, seasonal as well as decadal time scales and weather extremes. This aim is fully consistent with the FoPoZ, requesting deeper knowledge about and prediction of natural risks for adaptation and disaster management. Our activities are in line with the current federal research policy priorities and funding priorities.[24] The joint efforts of T1 and the BMBF funding priority 'Climate Change and Extreme Events (ClimXtreme) stimulate new research on the role of extreme events in a changing climate and make a significant contribution to the implementation of the federal High-Tech Strategy 2025.[25]

[18] See FoPoZ, Section 3, Topic 1.

[19] See ROMIC-II, https://www.bmbf.de/foerderungen/bekanntmachung-1438.html.

[20] The Africa Strategy of the BMBF; see https://www.bmbf.de/upload_filestore/pub/Afrika_Strategie_eng.pdf (June 2019).

[21] FONA: Forschung für nachhaltige Entwicklung (Research for Sustainable Development; see https://www.fona.de/de).

[22] This includes 'WASCAL II – West African Science Service Centre on Climate Change and Adapted Land Use', 'SPACES 2- Research partnerships for the adaptation of complex processes in the Earth system in the Southern African region', or 'GROW – Water as a Global Resource' of the BMBF.

[23] Also stipulated by FoPoZ, Section 3, Topic 1.

[24] This includes 'ClimXtreme – Climate Change and Extreme Events' or 'RegIKlim – Regional Information for Action on Climate Change', within the framework program FONA.

[25] See https://www.hightech-strategie.de/ (June 2019).

Participation in the BMBF priority program RegIKlim complements our comprehensive **knowledge transfer program** – as **stakeholder-tailored information** for regional climate adaptation in urban spaces, for the agriculture industry, or as knowledge synthesis via IPCC or IPBES. For a detailed view of our strategy-based knowledge transfer activities, see Section F. Our engagement in RegIKlim illustrates the timeliness of the T1 competence portfolio and research platform in regional Earth system modeling.

We will assume a formative role for this subject area in the PoF IV Helmholtz program and related international collaborative efforts, as suggested in the FoPoZ. Our **unique combination of infrastructures** (observational and modeling) fosters international co-operation and provides cutting-edge research and research-training options.

Function and contribution of the Topic within the Program. The atmosphere is the Earth system compartment through which humans affect climate most directly, and the atmosphere is the primary medium for substantial feedbacks of climate with the land surface, the biosphere, the cryosphere, and the ocean. Therefore, T1 will have a **leading role in the research effort on atmospheric processes and climate change impacts within the overall Program**, in close collaboration with T2, T3, T4, T5, and T7. This includes the investigation of atmospheric processes relevant for climate and air quality, as well as the exchange processes and feedbacks with the adjacent compartments. In consequence, T1 research has a major impact on 8 (of 10) overarching scientific objectives of the Program (see Ch. 5.1; Objectives 5, 7, 9, 10).

Thus, we anticipate a wide range of **collaboration with other Topics** of the Program, as well as with research groups in other Helmholtz Research Fields as an essential element of the Topic's efforts toward sustainable solutions. In particular, the defined collaboration with T2 provides new perspectives in this direction. Expected joint activities include:

- Climate change – ocean-atmosphere interaction, prediction (with T2, and DWD)
- Regional Earth system modeling (with T2 and T4, and DWD)
- Forecast and management of extreme events (with T2 and T3, and CCA Extremes)
- Space weather – atmosphere feedbacks (with T3)
- Climate adaptation, land use change, water availability, (with T5 and T7, and CCA TERENO)
- Air quality and human health (with HMGU, RF Health)
- Atmospheric sensing (with DLR, RF Aeronautics/Space/Transport)

The programmatic impact of these on-going and planned collaborations is described in more detail in Section C. In some cases the proposed joint projects contribute to formal collaborations in CTAs/CARFs, as described in Section F, but due to the existing portfolio of expertise in T1, we also expect additional informal contributions to interdisciplinary fields such as 'Biodiversity', or 'Deep Learning/Machine Learning', in collaboration with other Topics in the Program.

Highlights. T1 studies regionally explicit drivers and impacts of global change from the perspective of, or with a view to, the atmosphere. The fact that the research team contributing to T1 can address global change processes throughout the whole atmosphere, including its interaction with the adjacent Earth system compartments, is its most important strategic highlight. This whole atmosphere approach places T1 in a position to make valuable contributions to other Topics and the entire Program. We actively promote this strategic development as a decisive step towards truly integrated Earth System Science solutions for the societal challenges of global change. A related highlight is our combination of measurements, data analysis, and modeling in all our work, corresponding to the research methodology triad of observation – understanding – prediction. In this endeavor, we strive to address entire process- and event chains from the drivers of global change or extreme events to their ramifications for air quality, water resources, GHG budgets, ecosystem viability, and the risk of more extreme weather in a warmer world. In T1, this integration of our combined expertise and resources benefits enormously from the momentum created by progress in ongoing integrative initiatives like REKLIM, TERENO, MOSES, and ESM.

B) Main research and structural objectives

Research Objectives. T1 contributes to most of the overall Program objectives (see Ch. 5.1) . The common goal of all work in T1 is to establish the scientific foundation for global change mitigation and adaptation measures that are regionally explicit, effective, and applicable. This requires the reliable modeling of coupling processes and interactions between all Earth system compartments relevant for climate change (atmosphere, ocean, cryosphere, land surface and biosphere, socio-economics), particularly on decadal temporal and regional spatial scales. To reach this long-term goal, we will further develop modeling components of compartment-crossing processes, in conjunction with integrated observation programs, and synthesize them into coupled regional modeling systems. Clearly, this can be reached only in collaboration with other Topics and external partners and will likely persist beyond the PoF IV period. For PoF IV, we have defined three more specific objectives that motivate our Subtopic structure (Section C).

- Objective 1: **Assessment of future air quality and implications for human and environmental health in conjunction with climate change**. To achieve this objective, we will determine consequences of global change for sources, sinks and transformation processes that affect air quality and atmospheric composition (incl. GHG), as well as their impacts on health, economy, and quality of life.
- Objective 2: **Reliable projections and predictions on the interconnected future developments of climate, atmosphere, and land use at global to regional scales, to assess future living conditions and options for the sustainable use of resources.** For this objective, we will explore and quantify the feedback-web between physical, chemical, biological, and socio-economic processes and mechanisms in the Earth system, through the development of scale-crossing observation and modeling methodologies.
- Objective 3: **Improved predictive skill of natural hazards, like floods and droughts, with a strong application focus on adaptation to extreme weather and climate change, as well as disaster management.** Towards this goal, we will assess extreme weather events in terms of their predictability and trends in frequency and magnitude with climate change, through in-depth knowledge of atmospheric processes gained in observational programs (e.g., MOSES), new observational techniques and complex numerical modeling at unprecedented resolution.

Structural Objectives.

- Objective 4: Integration and enhancement of multi-purpose and modular observational infrastructure toward a **concerted 'system of systems' for atmospheric and climate research (ATMOsense, planned)**. Implementation of novel techniques for data assimilation will facilitate future approaches in model-data fusion.
- Objective 5: To build up both IT infrastructure and expertise in the emerging field of **environmental data science to an internationally leading level in atmospheric and climate research**, following a coordinated strategy across the Program.
- Objective 6: To assume an **internationally leading role in regional Earth system modeling, and a formative role in the emerging national strategy on Earth system modeling,** together with partners within the Program and the German research community at large. The planned new ATMOsense infrastructure will provide data for model evaluation across scales.
- Objective 7: Establishment of an **internationally leading structured qualification and talent management program in atmospheric and climate sciences**, including all levels from students, graduate students to junior group leaders. Building blocks of such a program (specific to T1 needs) already exist in the participating centers.

To achieve the proposed objectives, a **long-term development concept** has been initiated, including:

- new research platforms (see Section C),
- opportunities for junior investigators (see Section F),
- a co-operation strategy with core partners and stakeholders (see Sections D and F), and an
- enhanced competence portfolio development in defined fields (see below).

During PoF III, the Topic has pursued a process for **strengthening its competence in several strategically relevant subjects**, including: 'atmospheric sensing', 'clouds/aerosols', 'extreme weather/ climate extremes', 'atmospheric modeling across scales', 'land/ocean/atmosphere interface', 'land change and ecosystem/climate services' and 'urban spaces' with twelve new professorships, 15 externally-funded YIGs, sophisticated infrastructures and major collaborative research projects. These activities go along with a comprehensive co-operation strategy – together with long-term partners and stakeholders within and outside the Program (see Sections D and F).

The **management of such a Topic** with seven partners (including DWD and DLR) is a challenge in terms of joint research implementation, communication, and knowledge transfer. T1 relies strongly on the management expertise of the last ten years in the ATMO program, where five of the seven PoF IV partners were involved. Monthly telephone conferences, periodic reporting, and annual strategic workshops are the main elements for effective communication and co-operation in the Topic. Strategic developments are embedded in a high-level international benchmarking process to provide guidance for the continued examination and adjustment of the Topic's research direction. This flexibility serves to reach the Topic's deliverables and milestones. T1 is consensus-oriented, but in the case of disagreements, we will follow a conflict management policy (with defined communication pathways) established in the ATMO program.

C) Structure of the Topic and motivation of Subtopics

Introduction of Subtopics. T1 is **structured into three Subtopics** (ST) of strong scientific and societal relevance in atmospheric and climate research (Fig. 1.1). ST1.1 'Air Quality' examines sources, sinks, distribution and transformation processes of atmospheric trace substances that affect the health of humans, animals, and plants. ST1.2 'Climate Feedbacks' assesses climate drivers including CO_2 and other greenhouse gases, aerosols, land use change, and solar forcing, by analyzing their effects and feedbacks with temperature, atmospheric composition, the hydrological cycle, or the general circulation system. Based on that, ST1.3 'Future Weather and Extremes' investigates the future statistics/climatology of weather phenomena in a seamless approach from sub-daily to decadal scales, with a particular focus on changes in frequency and magnitude of extreme events.

The structure of the Topic serves to address: i) the most immediate societal impact from global change on the atmosphere (ST1.1), ii) the most complex challenge for dynamic climate system understanding (ST1.2), iii) the most relevant ambition for modeling and prediction of climate change consequences affecting everyday life (ST1.3). The three Subtopics correspond to the three T1 scientific objectives and are strongly inter-related, but express different aspects and perspectives of the atmosphere in global change. Work in the Subtopics will necessarily require broad cooperation across the Topic, and specific collaboration with other Topics (especially T2, T3, T4, T5, T7 and other Research Fields).

To fulfill the PoF IV Program mission, T1 operates and contributes to several excellently equipped observational and experimental research infrastructures, observation networks, and modeling systems. The infrastructures are one important prerequisite for the cutting-edge research in emerging fields of the STs (see Section D). These infrastructures are used mostly across all STs. They are either:

- operated by T1 (AIDA, KITcube, SAPHIR, ESFRI IAGOS), including service to the research community (mandated in FoPoZ),
- part of PoF IV scientific collaborations within the RF (TERENO, MOSES, MESI with GNSS),
- a prerequisite for T1's formative role in regional Earth system modeling on an (inter)national level with associated data management facilities (mandated in FoPoZ),
- our future contributions to long-term environmental observations in international networks (NDACC, TCCON, ICOS, FLUXNET, ESFRI ACTRIS, GCOS/GRUAN), or
- long-term strategic developments of new platforms (e.g., GLORIA-B AtmoSat, on the national roadmap; ATMOsense, planned).

TOPIC 1 | The Atmosphere in Global Change

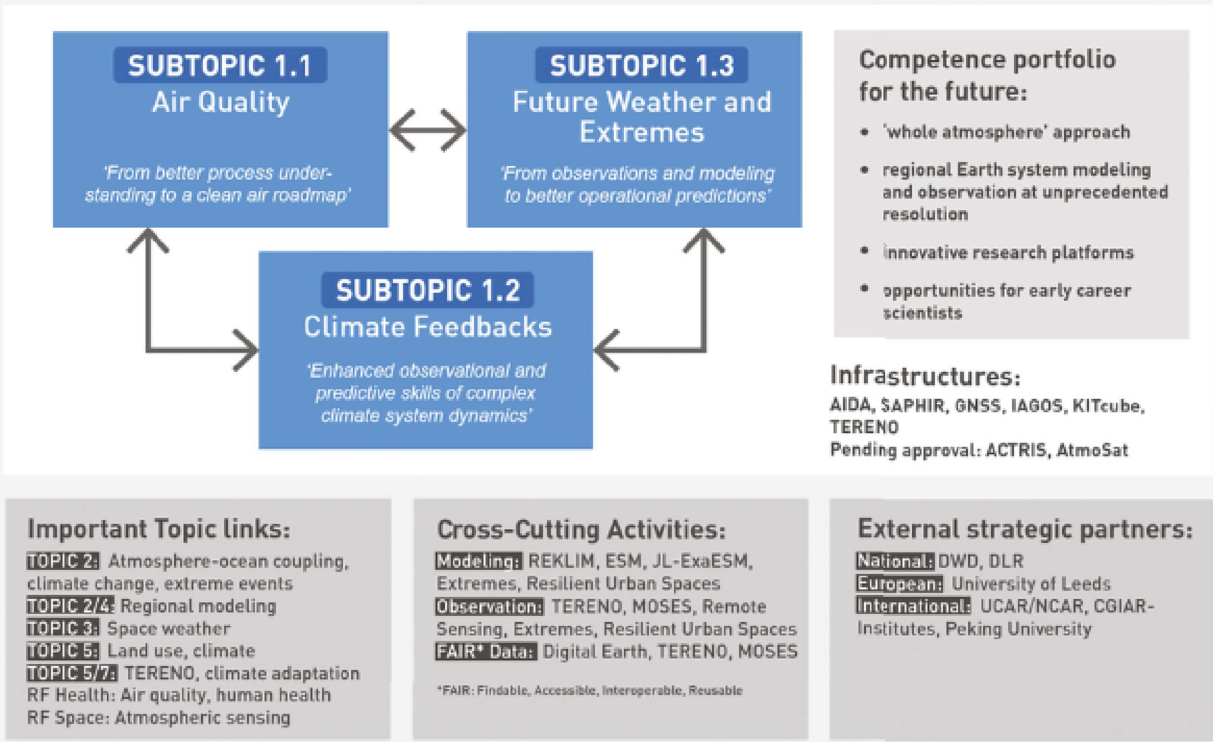


Fig. 1.1: Structure of T1 with its three Subtopics, along with a selection of critical links to other Topics, core CARFs and CTAs and strategic partners.

Contributions of the Centers to the Topic. **AWI** brings two land stations into the consortium, the Neumayer III Station in the Antarctic and the AWIPEV station on Spitsbergen. The latter is closely involved in international atmospheric research through a flagship program (Svalbard Science Forum). The Polar Aircraft of the institute are used with external partners for dedicated campaigns. **FZJ** has particular expertise in investigating climate-relevant processes in the upper troposphere and middle atmosphere, based on the development of process-oriented models (CLaMS), highly-sophisticated remote sensing (e.g., Gloria) and in situ instruments for airborne platforms (HALO, M55-Geophysica), and new-generation mini-satellite sensors. FZJ is specialized in the development of atmospheric chemistry mechanisms required for understanding the tropospheric composition and its changes. The center utilizes experimental simulation, field observation, theory, and regional to global modeling for its research. Unique infrastructures operated and coordinated by FZJ are IAGOS-CORE and the SAPHIR simulation chambers. **GFZ** provides unique contributions based on the application of innovative GNSS remote sensing, geomagnetic, and energetic particle observations with related modeling activities. These include the usage of operational data from regional and global ground networks, complemented by satellite observations mainly from COSMIC-1/2, Swarm, GRACE-FO, Lomonosov, mini-satellites, and potentially also AtmoSat. **HZG** and its Climate Service Center Germany (GERICS) are engaged in various research themes in the fields of regional climate-, impact, and economic modeling. Most relevant for T1 is the further development of the regional climate model REMO and its connection to socio-economics. **KIT** addresses the improvement of regional and global predictions/projections of climate and water availability, biosphere-climate interactions (especially regarding biospheric sources/sinks of GHG and land use in global change), the forecast of extreme weather events (particularly floods and droughts), the analysis and prognosis of air quality, as well as the future evolution of the ozone layer. With national and international partners from the public and economic sectors, KIT provides research with immediate relevance to society in the context of increasing demand for risk assessments related to climatic and atmospheric change. With this expertise, KIT contributes strongly to all three STs. The above-mentioned research at KIT is conducted mainly by its Institute of Meteorology and Climate Research (IMK), ranked 8th in the 2019 Shanghai Ranking.[26] The institute consists of four departments with 15 professorships at two sites (Karlsruhe and Garmisch-Partenkirchen). IMK operates large infrastructures, including TERENO-preAlpine, KITcube, and AIDA, Gloria on HALO and IAGOS/CARIBIC, as well as complex modeling systems and large data management facilities.

D) Subtopics

Subtopic 1.1 Air Quality

Astrid Kiendler-Scharr, FZJ; Peter Braesicke, KIT

Scope and challenges. The Subtopic Air Quality (ST1.1) addresses sources, sinks, and the distribution of atmospheric trace substances as well as their atmospheric transformation processes. The activities of Air Quality provide the scientific input for the development of a clean air roadmap benefitting likewise human health and ecosystems, as well as climate change mitigation. Thereby ST 1.1 breaks new ground in the development of fundamental understanding of atmospheric composition and its use in the societally and politically relevant theme of air quality.

Air quality, here defined in a wider sense to cover aspects of atmospheric composition and pollution, is the result of atmospheric physical and chemical processing of anthropogenic and biogenic emissions, and atmospheric transport over larger distances (Fig. 1.2). Problems of air quality are determined primarily by the conversion of reactive trace species to secondary pollutants such as ozone and secondary fine particles, evoking temporal and spatial dimensions from seconds to years and from local to global. Many air pollutants are scientifically challenging through their dual role as atmospheric health hazards and as short-lived climate forcers (SLCF), causing complex atmospheric chemistry-climate interactions. This is particularly relevant for air pollutants originating from emissions, which in themselves depend on weather and climate.

Research in ST1.1 contributes strongly to internationally organized research and assessments. Important links exist with Copernicus, the European Union's Earth Observation Program, CAMS (Copernicus Atmosphere Monitoring Service) for regional air quality forecast systems development and operation, WCRP-CORDEX, CSP – Climate Service Partnership and TOAR, IPCC, LRTAP, and WMO assessments. IAGOS is a major contributor to the Global Atmosphere Watch Program of WMO and various COPERNICUS services (Atmosphere Monitoring, Climate Change Service).

Main objectives. The scientific goals of ST 1.1 are to quantify the distribution of secondary pollutants in current atmospheric chemistry regimes and to project future changes in atmospheric composition with emphasis on climate-induced changes.

To predict future air quality, we need to understand emissions and their changes in the context of climate change, an evolving energy and transport system, urbanization and land use change, interactions of anthropogenic and biogenic emissions in atmospheric chemistry, and the spatial and temporal scales of atmospheric chemistry-climate interactions (linking all STs).

Work program. Developing process-level understanding of conversion mechanisms and implementing this knowledge in regional and microscale chemical weather forecasts, is a cornerstone of ST 1.1. This process-level understanding is derived from observations i) at air quality hot spots such as mega-cities, ii) across the planetary boundary layer and free troposphere globally, and iii) in innovative simulation chambers dedicated to the exploration of atmospheric chemical mechanisms. Observationally driven chemical mechanism development is complemented by theoretical approaches, including quantum chemical simulations and investigations of the interplay between atmospheric transport processes and chemical reactions.

[26] See http://www.shanghairanking.com/shanghairanking-subject-rankings/atmospheric-science.html (July 2019).

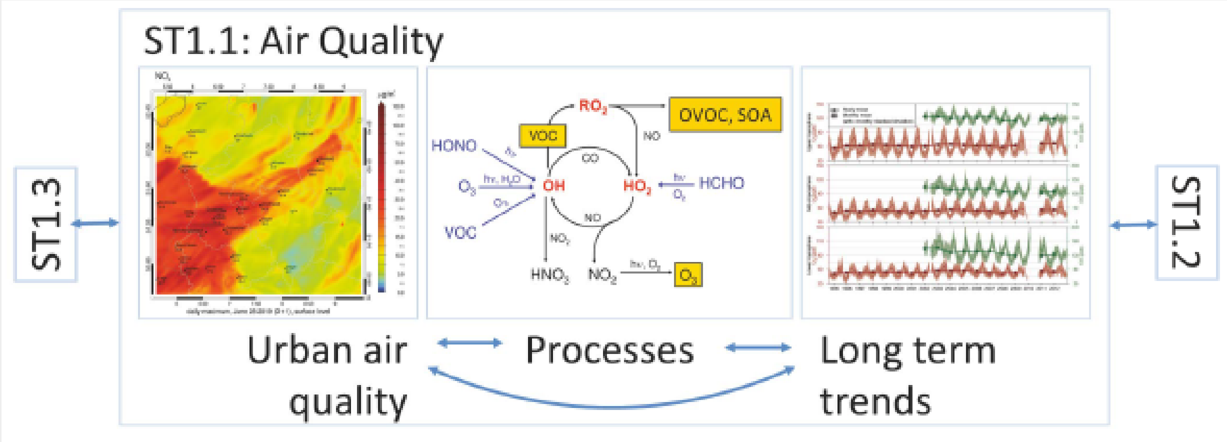


Fig. 1.2: Workflow of Subtopic 1.1, establishing new process understanding of atmospheric chemistry to link climate and air pollution.

The work program of ST1.1 will facilitate the development of process understanding towards impact analysis from the local to global scale with deliverables serving societal needs and the science community. To this end, ST1.1 will i) develop a high-resolution urban air quality inventory, ii) develop a radical and secondary pollutant air quality metric for mitigation and adaptation strategies, and iii) determine global and long-term trends of atmospheric composition within the Earth system.

Urban air quality (FZJ, HZG, KIT). Since 2007, the majority of the world's population lives in cities, and the trend towards increasing urbanization is projected to continue to about 60% by 2050.[27] Many physical changes such as intensifying urban heat island effects and an increase of intensity and frequency of heavy precipitation are already studied, yet it is often unclear how climate change impacts are affecting air quality in cities and vice versa.[28] In addition, air quality in cities is heavily influenced by other aspects apart from climate change such as emission changes from, for example, heating, transport, or industry.

Developments in this work package will inform cities about their air quality options by a combined approach of i) high-resolution local observations of urban and background air quality, ii) street-level air pollution prediction with microscale (PALM-4U) and regional modeling (WRF-Chem, ICON-ART, EURAD-IM), and iii) a module for GERICS' adaptation toolkit for cities that will support urban planning in a changing climate with respect to air quality. Important aspects during the process will be the combination of regional climate information with air quality, involving new techniques of big data analytics and other city-relevant information (such as environmental aspects, traffic concepts, alternative fuels, and fleets) in a holistic approach. This work will be done in close cooperation with local stakeholders for proper co-design and co-development of the air quality module to address the user needs optimally.

Atmospheric chemistry processes (FZJ, KIT). Our ability to predict the self-cleaning efficiency of the atmosphere and the formation of secondary pollutants (e.g., ozone and fine particles) depends crucially on our understanding of the chemistry and abundance of free radicals (OH, HO_2, organic peroxy radicals RO_2) in the atmosphere. In the last five to ten years, combined field observations, chamber experiments, and theory have led to the discovery that a significant proportion of atmospheric RO_2 can undergo unimolecular isomerization and O_2 addition reactions (autoxidation). Autoxidation reactions of specific RO_2 can reform OH or HO_2 without producing ozone,[29] or can produce highly oxidized molecules (HOM) as precursors of secondary organic aerosols (SOA).[30] Furthermore, it has been recently shown that in atmospherically relevant mixtures specific

[27] United Nations 2018. World Urbanization Prospects. 2018 Revision – Key facts, United Nations, New York.

[28] *Fallmann J, et al. 2016. Secondary effects of urban heat island mitigation measures on air quality. Atmos Environ. 125(2016):199e211 [Note: The symbol '*' indicates publications of Program members.].

[29] *Fuchs H, et al. 2013. Experimental evidence for efficient hydroxyl radical regeneration in isoprene oxidation. Nature Geoscience. 6:1023–1026.

[30] *Ehn M, et al. 2014. A large source of low-volatile secondary organic aerosol. Nature. 506:476–479.

interactions between organic RO_2 suppress SOA formation,[31] challenging current model representations of SOA formation.

Systematic research of the underlying autoxidation mechanisms has just begun, and progress in this emerging field requires sophisticated experimental and theoretical methods to explore the chemistry of reactive gas species, intermediate products, and particles.

This work package therefore combines i) field observations on the ground (JULIAC, KITcube-aerosol), in the planetary boundary layer (UAVs, Zeppelin NT), ii) simulation chamber studies (SAPHIR, SAPHIR-PLUS, SAPHIR-STAR, AIDA, AIDA-dynamic), iii) theoretical chemistry, and iv) regional (EURAD-IM, ICON-ART) and global modeling (EMAC, ICON). Some of the field experiments will be conducted in polluted regions in China in cooperation with Peking University (PKU) within the International Joint Research Lab of FZJ and PKU.

Long-term trends of global atmospheric composition (FZJ, KIT). The long-term observation of the changing atmosphere in the Anthropocene, with particular consideration of the essential climate variables, is one of the key challenges in the upcoming decade. High-quality observations on a global scale are urgently required for the assessment of the current level of climate change, and the development and review of implemented mitigation strategies and potential international agreements like the Paris Agreement 2015. In this context, trustable attribution of different sources and processes to global greenhouse-gas budgets and their trends is one of the main open questions, with short-lived climate forcers posing particular challenges due to their relatively large spatial and temporal variability and their dual role as air pollutants.

Thus, this work package performs i) ground-based long-term near-IR solar FTIR measurements of CO_2 and CH_4 within the TCCON network (Garmisch and Zugspitze, plus partner sites) representative for the regional to hemispheric scale and column soundings of other tracers via NDACC-type (mid-IR) to support source attribution, and ii) long-term in situ measurements of the chemical composition in the UTLS aboard a fleet of instrumented civil aircraft (IAGOS-CORE) and the IAGOS-CARIBIC aircraft. In-depth observation-model comparison (using ICON-ART and EMAC), based on various metrics in different regions and altitudes will allow a multifaceted assessment of our current understanding on the fate of various pollutants and trace substances and the controlling processes.

Deliverables (D) and Milestones (M)

- **D1.1 (2027)**: High-resolution inventory of urban air quality. **M1.1-1 (2023)**: Validation of the high-resolution model of urban air quality (PALM-4U) under current emission conditions. **M1.1-2 (2025)**: Statistical analysis of air quality risk conditions for future projections.
- **D1.2 (2027)**: Radical and secondary pollutant air quality metric. **M1.2-1 (2024)**: Unified parameterization scheme for gas to particle partitioning accounting for condensation, evaporation, accretion reactions, and particle-phase state. **M1.2-2 (2026)**: Exploration of peroxy radicals as an integral parameter for air quality metrics.
- **D1.3 (2027)**: Assessment of global and long-term trends of atmospheric composition. **M1.3-1 (continuous activity with regular updates)**: Steady and enhanced global observation of atmospheric composition and investigation of tropospheric concentration trends as contribution to the United Nations´ Task Force on Hemispheric Transport of Air Pollution and SPARC. **M1.3-2 (2027)**: Evaluation of anthropogenic impact on atmospheric composition in the context of socio-economic change, focusing on NO_2 and particulate matter vertical profiles for various regions of the Earth.

Infrastructures and specific resources. Research in ST1.1 builds on the use and development of large-scale experimental and computing infrastructures as detailed in the respective WPs.

Within the PoF IV funding period, ST1.1 will expand measurement capabilities to trace species of relevance in the context of the 'Energiewende' (German energy systems transformation) and a changing mobility system. Effective 'tailpipe' emission control for many industry, energy, and transport sectors will result in a larger contribution of regional sources to local air quality, emphasizing the need for techniques to measure atmospheric chemical aging. Special attention will be given to species connected to atmospheric acidity and its change due to continuous increases in NH_3 emissions and effective emission control of SO_2 and NO_x.

[31] *McFiggans G, et al. 2019. Secondary organic aerosol reduced by mixtures of atmospheric vapours. Nature. 565:587–593.

The European Research Infrastructure IAGOS, with its components CORE and CARIBIC, will be further extended towards the inclusion of critical regions (e.g., Arctic, Southern Pacific) of the Earth system into the existing observation network. The implementation of FAIR data services and management in IAGOS for both CORE and CARIBIC components is currently underway as part of the CCA Digital Earth and the European Horizon 2020 project ENVRI-FAIR, coordinated by FZJ. On the technical side, observation capabilities will be enhanced by the transfer of IAGOS instrumentation to the new carrier platform Airbus A350.

A modified Zeppelin NT has recently been established in cooperation between Zeppelin Luftschifftechnik (Friedrichshafen) and FZJ for in situ observations over different regions in Europe during the EU project PEGASOS.[32] Further deployments of the Zeppelin NT for boundary layer air quality studies in the PoF IV period are planned.

Within Helmholtz, competences in the development and application of atmospheric chemical mechanisms for Earth system modeling are bundled in ST1.1, which constitute a core element for the national strategy on Earth system modeling.

Cooperation partners. Within the Program, ST1.1 is a partner in the CTAs REKLIM, MOSES (AG Heat Waves), ESM (WP1 Earth System Model Development and WP3 Frontier Simulations), and DE (AG Global Observation).

CARFs exist with Helmholtz partners at HMGU for the investigation of biogenic volatile organic compound emissions. In the framework of CARF MACE and the Helmholtz International laboratory AeroHEALTH, the health effects of air pollutants are investigated in collaboration with the Helmholtz RFs Health and Information (see Section F for details). Air quality aspects are also central to HI-CAM adaptation and mitigation activities and CARF Resilient Urban Spaces. Strategic partnerships involve national universities such as the University Hannover and FU Berlin for the development of PALM-4U, University of Heidelberg for FTIR remote sensing techniques, international universities such as Stockholm University for aerosol studies, University of Toulouse and University of Manchester for IAGOS, and the PKU in the International Joint Laboratory on Atmospheric Chemistry.

Subtopic 1.2 Climate Feedbacks

Almut Arneth, KIT; Martin Riese, FZJ

Scope and challenges. ST1.2 assesses options that emerge, especially from the Paris Climate Change Agreement goals, to limit mean global warming to well below 2°C above pre-industrial levels and strengthen capacities to adapt to climate change. Judging the achievability of temperature targets through policy action requires resolving the existing large uncertainties of global warming in response to increasing GHGs and changes in aerosols and land use.

These main climate drivers influence atmospheric dynamics, cloud and precipitation formation, and the radiation field in intricate nonlinear feedback loops that are not confined to specific atmospheric layers but extend throughout the entire atmosphere and are constrained by the interaction with the neighboring compartments land surface, ocean, cryosphere and near-Earth space (c.f. Fig. 1.3).

Main objectives. The main objective of ST1.2 is to unravel and quantify these feedbacks and interactions, in more detail and with improved temporal and spatial resolution, to significantly enhance the predictive power of future climate projections. This requires a concerted approach reaching from laboratory studies via field observation and utilization of satellite observations to high-resolution modeling.

ST1.2 research is closely aligned with international institutions, programs and initiatives such as the World Meteorological Organization (WMO), Stratospheric and Tropospheric Processes And their Role in Climate (WCRP-SPARC), the International Space Science Institute (ISSI), Future Earth, COSPAR, SCOSTEP, IPCC, and IPBES. The international orientation of the Subtopic further benefits from long-standing collaborations with other leading international research organizations and universities.

Specific scientific objectives are:

1. Quantification of impacts of land use change and climate change on water availability and terrestrial GHG emissions, associated with diverse land use sectors, identification of related feedback mechanisms, and

[32] *Li X, et al. 2014. Missing gas-phase source of HONO inferred from Zeppelin measurements in the troposphere. Science. 344(6181):292–296.

development of concepts for environmentally sound management of natural resources under conditions of global change.

2. Quantification of changes in atmospheric composition (including clouds) and circulation patterns (including Monsoon systems and Brewer-Dobson circulation) in a changing climate and improved representation of underlying processes in Earth system models.
3. Quantification of process chains that involve the stratosphere and the ocean, to improve our understanding of decadal variability down to seasonal and sub-seasonal predictability and to enhance the quality of regional climate change projections in Earth system models.
4. Quantification of forcing from below (atmosphere) and above (solar, magnetosphere) of the dynamics and composition in near-Earth space, and investigation of feedback mechanisms with the lower atmosphere.

Work program. To achieve the scientific objectives, the work in ST1.2 is organized into four work packages, which are closely interlinked. As a major advance compared to PoF III we will study coupling mechanisms across all relevant spatial- and temporal scales between terrestrial ecosystems, oceans (link to T2) and the whole atmosphere (surface to upper atmosphere). This approach is essential for improved projections of regional climate change and sub-seasonal to seasonal predictions (links to ST1.1 and ST1.3). The 'whole atmosphere' approach also allows investigation of interactions between the (non-charged) neutral atmosphere and the ionosphere (relevant for space weather, link to T3). A strong connection to T2 is created by investigating stratospheric impacts on regional climate with a link to the ocean.

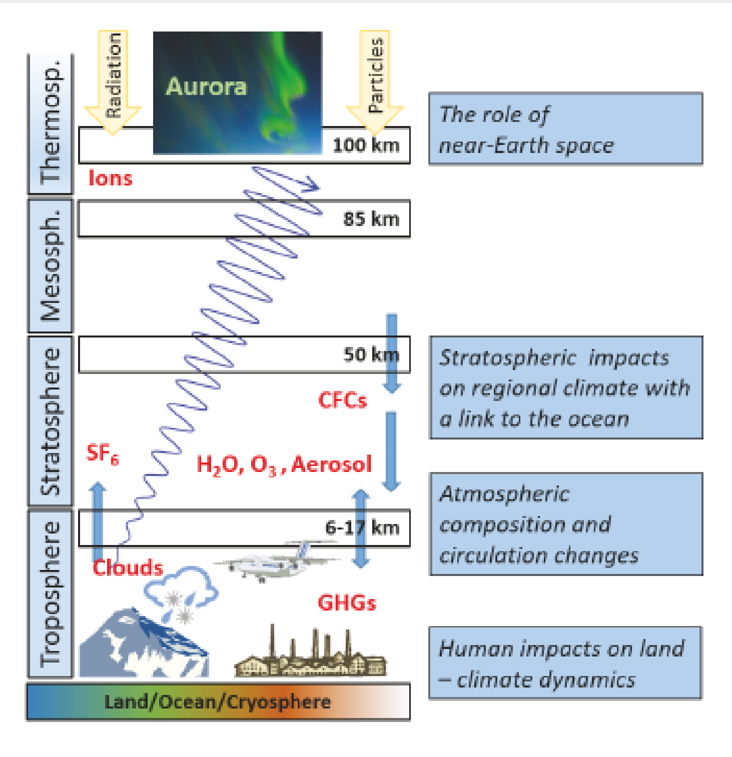


Fig. 1.3: Subtopic 1.2 investigates drivers of climate change and feedbacks across all relevant spatial- and temporal scales between terrestrial ecosystems (links to T5, T7), oceans (link to T2) and the whole atmosphere (surface to upper atmosphere). The 'whole atmosphere'-approach is essential for improved projections of regional climate change and sub-seasonal to seasonal predictions (links to ST1.1 and ST1.3). It also allows investigations of interactions between the neutral atmosphere and ionosphere (relevant for space weather, link to T3).

Human impacts on land – climate dynamics (KIT, FZJ, HZG). To cover the increasing demand for crop, livestock, fiber products as well as bioenergy by an increasing world population, natural ecosystems are increasingly converted to managed systems, and agricultural and forest production is further intensified. Agriculture accounts for 70% of the total freshwater consumption worldwide. It is also estimated to contribute about one-quarter of the global anthropogenic GHG emissions. However, agricultural and natural ecosystems are not only sources and sinks for GHGs, but dynamically respond to climate change in a non-linear fashion. Exceeding environmental tipping points might lead to major breakdowns of ecosystem functions and result in, e.g., desertification or the loss of tropical forests and savannahs. Therefore, it is of crucial importance to understand the interlinked processes between water fluxes and GHG emissions for managed and natural ecosystems and their feedbacks to the atmosphere and the climate system.

While climate change and accompanying changing environmental conditions are jeopardizing food production, especially in regions that already suffer from climate change impacts, strategies need to be identified to increase agricultural production sustainably (i.e., at lower environmental costs and decreased risks of failure, including mitigation co-benefits). This large challenge for human societies asks for increased societal awareness of the climate footprint of food production, reflections on the resources used for different diets, functions of ecosystems, and robust assessment of environmental consequences of region-specific water-, ecosystem- and land management options, to support political decision-making processes.

We will study how human activities and climate change are jointly affecting regional-scale water cycling and the exchange of climate-relevant trace gases (CO_2, CH_4, N_2O, VOC or NO_x) between the biosphere and atmosphere, on the global scale, as well as with a focus on selected climate-sensitive regions. Specifically, we aim to identify and understand feedback mechanisms to improve predictions of land-climate dynamics in response to global change.

Atmospheric composition and circulation changes (FZJ, KIT, GFZ, AWI). We aim to quantify the most important atmospheric feedbacks (e.g., clouds, water vapor, ozone, circulation) and the underlying processes. Clouds are currently one of the largest sources of uncertainty for modeling climate change, as cloud cover and cloud optical properties react strongly on circulation change and changes in the aerosol distribution. Work on ice formation in clouds will concentrate on laboratory work in the AIDA facility. The newly developed AIDA dynamic chamber will allow the assessment of slow ice growth and multiplication processes under well-defined turbulence conditions. From this, we will derive parameterizations that can be used in cloud-resolving models. Increasing water vapor concentrations in response to global warming form a major positive feedback in the climate system with the largest uncertainties associated with changes in the upper troposphere and stratosphere (UTLS). Decadal-scale variability of water vapor will be studied based on observational (aircraft, balloon, satellite) and model data.

The North Polar Region is characterized by rapid warming ('Arctic Amplification'). Hence, measurements and modeling of aerosol, its pathways into the Arctic, radiative forcing and interaction with clouds will be investigated. For Antarctica, the situation is more complex. Here, the high cloud cover under pristine conditions will be investigated.

Transport of water vapor and pollutants by the Asian monsoon circulation represents a major uncertainty in global chemistry-climate interactions. This problem is of particular importance because the strong population growth in Southeast Asia and the associated rapid economic growth cause increasing regional and global pollution of the atmosphere (link to ST1.1). This will be addressed by a combination of new high-precision measurements (e.g., future HALO campaigns) and process modeling. Global impacts will be assessed by carrying out novel Earth system model frontier simulations within the ESM activities (link to T2).

Changes in the Brewer-Dobson circulation (BDC) represent a crucial factor for the Earth's climate, as they influence the UTLS greenhouse gas distribution. The strength of the global BDC is affected by anthropogenic climate change (i.e., rising GHG concentrations), random forcing by volcanic eruptions, as well as by various modes of natural variability (e.g., ENSO, QBO, and solar cycle). However, the different representations of these effects in global models lead to large uncertainties, which we strive to narrow down. We will compare current meteorological reanalysis data sets and model simulations with chemistry-transport and chemistry-climate models, focusing on separating natural variability from long-term (anthropogenic) changes. In particular, feedbacks between changing stratospheric tracer distributions, radiation, and dynamics will be quantified from the model simulations. Contributions of gravity waves to BDC variability and trends will be studied based on observational and model data.

Stratospheric impacts on regional climate with a link to the ocean (KIT, FZJ, GEOMAR, AWI). The troposphere is 'sandwiched' between the Earth surface and the stratosphere. Thus, stratospheric variability is a key influence on tropospheric weather and climate. Consideration of processes on sub-seasonal to decadal timescales in the stratosphere enhances seasonal predictability for tropospheric circulation patterns, which in turn provide a driving force to the ocean. In cooperation with T2, we will investigate processes and their impacts that are traceable from the ocean through the atmosphere – and in particular to the stratosphere (and vice versa) – and how they affect regional climate and regional climate change (input to REKLIM).

With new climate simulations, we will study the coupling processes between the stratosphere and troposphere on different time scales (sub-seasonal to decadal). Transport will be improved by either coupling a Lagrangian scheme to or increasing resolution of comprehensive climate models. Effects of such improvements on dynamics and downward coupling will be analyzed.

The role of near-Earth space (GFZ, FZJ, KIT). The atmosphere extends to altitudes of a few hundred kilometers, where neutral gas thermodynamics and electrodynamics of ionized gas affect satellite operation and radio wave navigation. We will investigate vertical coupling through atmospheric waves between the lower, middle, and upper atmosphere, and solar forcing on the ionosphere. To quantify these effects and feedback mechanisms, we develop statistical data analysis methods, event detection algorithms, and global models.

Energetic particles that precipitate from the magnetosphere can have a profound effect on nitric oxide, with consequences for ozone and climate. To quantify the effects of particle precipitation, we will need to understand and quantify the dynamic evolution of energetic particles and their effect on upper-atmospheric chemistry.

Deliverables (D) and Milestones (M)

- **D1.4 (2025):** Scenarios for regional and global land use and management to cope with the challenge of environmental and societal changes. **M1.4-1 (2023):** State of contributions of food systems to regional and global climate change assessed and mitigation options identified.
- **D1.5 (2027):** Assessment of solar-terrestrial processes taking place in the near Earth's space, and of its possible feedback mechanisms on lower atmosphere dynamics. **M1.5-1 (2025):** Vertical wave coupling in the atmosphere versus solar influences on weather and climate of the upper atmosphere assessed.
- **D1.6 (2027):** Sub-models and parameterizations for improved representation of dynamical, chemical, and micro-physical processes in atmospheric and Earth system models. **M1.6-1 (2023):** Assess variability of circulation systems and underlying processes across time scales. **M1.6-2 (2025):** Dynamical couplings between stratosphere and troposphere analyzed (based on observations and simulations). **M1.6-3 (2025):** Simulations focusing on the role of the Asian Monsoon in global chemistry-climate interactions (ESM project) are evaluated (link to T2).
- **D1.7 (2027):** Regional and global assessments of soil-vegetation-atmosphere feedbacks and changing water pathways and -residence times under increasing GHG- and land use change scenarios. **M1.7-1 (2023):** Current state of contributions of food systems to regional and global climate change assessed and mitigation options identified. **M1.7-2 (2025):** Scenarios for regional and global land use and management to cope with the challenge of environmental and societal changes. **M1.7-3 (2027):** Parametrizations for the glaciogenic properties of the most important types of atmospheric aerosols derived from laboratory experiments.
- **M1.8 (2027):** Quantitative representation of complex biogeochemical processes and human management effects in Earth system- and climate models used for detailed scenario analyses.

Infrastructures and specific resources. The scientific analyses are based on the synergetic use of airborne and ground-based observational data and networks, chamber experiments, satellite observations, process-oriented simulations, and Earth system modeling. In addition, long-term data sets are provided to the community (e.g., 20 years of past airborne water vapor and cirrus cloud observations).

Ground-based networks include ICOS, TERENO, NDACC, TCCON, ACTRIS (proposed), GNSS, geomagnetic, and VLBI observatories. We assess cloud properties, ice fraction, ice cloud formation, and precipitation by the installation of a new cloud observatory at the Antarctic Neumayer Station III (AWI). To study cloud-climate interaction, we use our AIDA facility (including the newly developed chamber AIDA-dynamic) of KIT.

For atmospheric composition studies we use remote sensing (e.g., GLORIA) and highly precise in situ instruments (e.g., FISH) for aircraft (e.g., HALO, GEOPHYSICA, Polar Aircraft), large stratospheric balloons (e.g., GLORIA-B) and small balloons containing miniaturized payloads consisting of a frost point hygrometer (water vapor detection), an optical backscatter instrument (ice cloud detection), an ozone instrument and a standard meteorological radiosonde. These observations will be complemented by AirCores providing tropospheric and stratospheric profile data on methane, carbon dioxide, other GHGs, and a number of age-of-air tracers.

The global view is provided by our satellite observations (e.g., MIPAS, GRACE-FO, Swarm), which are complemented by observations of MLS, SABER, ACE-FTS, AIRS, COSMIC-1/2, Lomonosov, etc. These instruments also provide crucial information on atmospheric dynamics. In the framework of the INSPIRE initiative (International Satellite Program in Research and Education), which aims to bring together students, scientists and engineers with industry and space agencies, FZJ and partners (BUW, MPI Erlangen, PTB) provide miniaturized SHI (Spatial Heterodyne Interferometer) based remote sensing instruments, to measure vertically resolved temperature profiles in the middle and upper atmosphere for INSPIRE Sat-3 and -4 and several follow-on missions.

Process-oriented atmospheric simulations (transport, mixing, ice clouds) are made with the global Chemistry-Transport-Model CLaMS developed at FZJ. Model development and co-development for land-climate dynamics (KIT) are based on LPJ-GUESS, LandscapeDNDC, WRF/WRF-Hydro, MPAS, PALM. Current chemistry-climate simulations are based on the EMAC or the ICON-ART model system. KIT and FZJ are members of the EMAC-consortium, led by our associated partner DLR-IPA. In addition, KIT has been developing the ART module for ICON-ART in close collaboration with the original ICON developers DWD (associated partner) and MPI-M. One strategic decision is the transition from ECHAM based models (e.g., EMAC) to ICON and its ESM configurations.

The increasing complexity of models calls for ongoing development, maintenance, and management and requires close links to HPC centers. Similarly, the administration of codes and management of data cause new challenges. Thus, our work relies on the availability of powerful and easily accessible supercomputing resources which are provided within Helmholtz through the Jülich Supercomputing Center (JSC), Karlsruhe Steinbuch Centre for Computing (SCC), and Hamburg 'Deutsches Klima-Rechenzentrum' (DKRZ).

Cooperation partners. An underpinning co-operation within the Program is via the CTA ESM and the CARF JL-ExaESM (RF Information; HPC for ESM), which supports high-performance computing for Earth system modeling. Other integrating activities concern regional climate modeling (REKLIM), the joint observational platforms TERENO and MOSES and CTA DE, and evolving data initiatives (e.g., ATMO Data Hub, part of the RF E&E Data Hub) as well as planned contributions to NFDI4Earth, and knowledge transfer activities (climate offices, SynCom). ST1.2 has strong interactions with our associated partner DLR-IPA in the fields of airborne observations (HALO, IAGOS) and Earth system modeling. Close cooperation with the new DLR Institute of Solar-Terrestrial Physics (DLR-SO, founded in 2019) is also planned.

Subtopic 1.3 Future Weather and Extremes

Christoph Kottmeier, KIT; Jens Wickert, GFZ

Scope and challenges. Ongoing climate change will affect not only the mean state and variability of the Earth's atmospheric state but will also alter the frequency, intensity, and character of weather events. Both weather variability and its modulation in a warming climate can be attributed to a complex combination of changes in large-scale atmospheric circulation, teleconnections, the hydrological cycle, atmospheric composition and interactions with the ocean and land surface. It is difficult to quantify how weather extremes will affect human living conditions on regional to local scales in a warmer climate.

This Subtopic addresses weather extremes under climate change as key scientific and societal challenges, as emphasized in the FoPoZ. Our main scientific challenge is to assess how and why the day-to-day weather, as well as extreme weather events of high impact, will change in a warming climate. Making progress requires detailed investigation of the physical processes governing weather variability and extremes across scales, ranging from sub-daily, synoptic, sub-seasonal, seasonal and decadal scales. This requires a better understanding of the driving physical processes. ST1.3 will address this challenging multi-scale problem with a seamless approach that integrates comprehensive observations and complex modeling systems with socio-economic impacts that leads to better predictions of weather, weather extremes and climate, which can inform adaptation strategies. This will be achieved by unprecedented model resolution and estimates that are more robust, by generating large model ensembles.

A main societal challenge is the mitigation of, and adaptation to, climate change. Heavy and/or prolonged precipitation can cause flooding or dangerous snow accumulations, while strong winds can severely damage forests and infrastructure. Droughts and heat waves negatively affect human health, agricultural production, and river transportation systems. The ability to predict the weather and weather-related phenomena (e.g., dust storms, volcanic ash dispersion) on sub-daily to synoptic time scales may save lives and infrastructure. ST1.3 will focus on the socio-economic impact of extreme weather events in a warming climate. While forecasting individual weather systems on sub-seasonal to decadal time scales is impossible, shifts in occurrence probabilities of extreme events can be estimated, and support planning processes.

Main objectives. The following objectives are stepping stones in a strategy (Fig. 1.4) to meet the challenges detailed above:

1. Develop and apply **new observational systems** on convective and synoptic weather systems and foster cross-platform integration. Atmospheric observation capabilities across scales and observation techniques are combined with modeling studies towards a better understanding of microphysical processes (AIDA) and mesoscale processes (KITcube). High-resolution models will allow us to bridge multiple spatial and time scales and to closely link with high-resolution observations, both from space and ground based.
2. Advance our **atmospheric and Earth system modeling** systems ICON/ICON-ART at the regional scale, with appropriate assimilation techniques and confronting the models with integrated observations. The focus is on enhanced spatial and time resolution (towards the km scale) and on aerosol and gas-phase processes not yet included in the modeling system.
3. Push the practical **limits of predictability** based on new modeling capabilities towards the provision of improved quantitative seamless forecasts of weather, composition, and extremes across scales, including those not yet covered by operational DWD services, e.g., sub-seasonal and decadal prediction. The focus ranges from local and regional weather forecasts of individual high-impact weather events to shifts in the occurrence frequency of extremes on climatic time scales.
4. Transfer the advances in weather and climate modeling for quantitative **impact predictions** towards tailored information for climate change adaptation. Special attention will be given to regions of high vulnerability and climate change hot spots (e.g., southern Europe, West Africa) and quantification of impacts associated with extreme weather.

Research in ST1.3 makes substantial contributions to internationally organized research agendas of WCRP and WWRP. This includes projects such as the High Impact Weather Project (HI-Weather), the sub-seasonal to seasonal (S2S) project, and CORDEX Flagship activities, which are closely linked to and strongly supported by ST1.3 researchers. Research is conducted in co-operation with our associated partner DWD and the European Center for Medium-Range Weather Forecasts (ECMWF) and is linked to the COPERNICUS climate service.

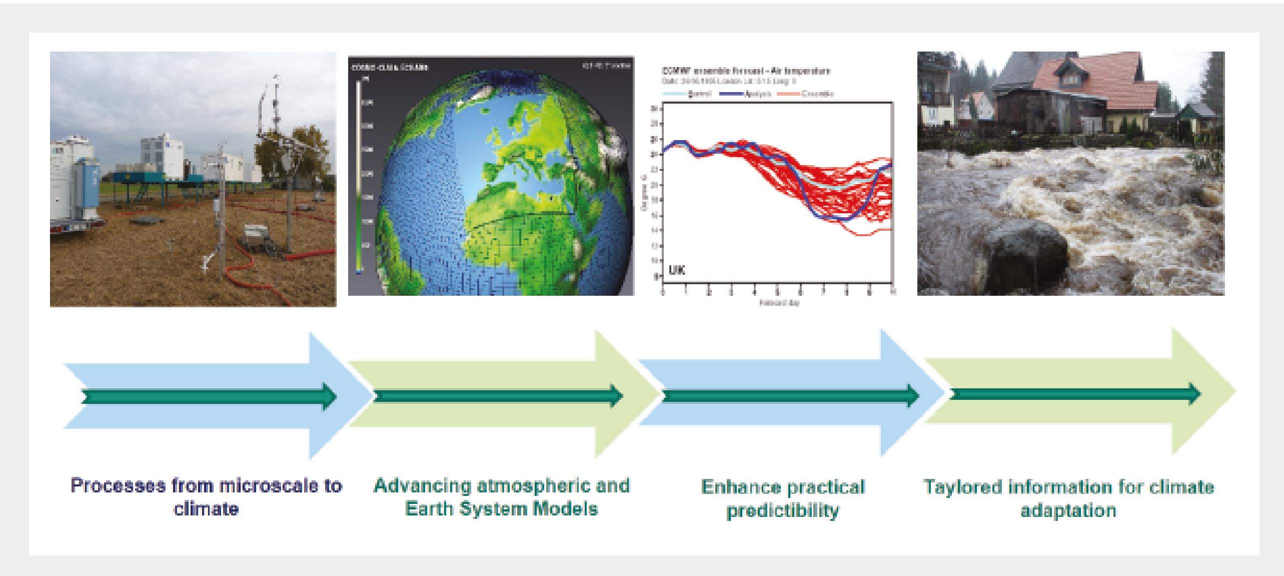


Fig. 1.4: Subtopic 1.3: The strategy comprises the whole chain of knowledge acquisition and use of experimental process research, model development and application, and discourse-based knowledge transfer to stakeholders.

Work program. The Work Packages are defined to effectively achieve the objectives listed above.

New observational systems and cross-platform integration within international field campaigns (KIT, GFZ). Existing multi-scale atmospheric observation systems (AIDA, KITcube, CARIBIC, Inside Clouds) as well as networks and satellite information (GNSS, Copernicus satellites) will be combined to create new synergies, such as on integrated observation of cloud systems in cooperation with international partners, based on recent developments (e.g., FCW water vapor lidar) and sensor synergies.[33] The extended observational, experimental and cloud simulation capabilities will be used to achieve an in-depth understanding and formal description of aerosol and cloud processes, in particular, those of relevance for precipitation development. On larger scales, water isotopes will be used as tracers for cloud and precipitation processes. The impact of the regional and temporal variability of aerosols and ice nucleating particles will be studied under real-world conditions with KITcube in situ observational capabilities (Inside Clouds), and clouds characterized by satellite remote sensing data. The spatiotemporal resolution and accuracy of GNSS atmosphere sounding observations for the regional and global scale will be significantly improved using data from upcoming new navigation satellite systems. GNSS-Reflectometry will be developed for innovative observations over land, sea, and ice in co-operation with T2. This WP will take part in many national and international field campaigns (e.g., MOSES, Alpine Experiment TeamX). This WP contributes with milestones M1.8-2, M1.10-1 and to deliverables D1.8, D1.10 (CTA MOSES, CTA Extremes).

Advancing atmospheric and Earth system models (KIT, HZG, AWI). The modeling strategy is to develop and apply the next generation of regional atmospheric and Earth system models with kilometer-scale resolution, to allow for fewer parameterizations and better coupling between small-scale processes. This will be based on, and in turn will lead to, enhanced process understanding and a more natural link with observations. Model systems include ICON, with ICON-ART, ICON-CLM and ICON-LEM versions; complemented by WRF/WRF-Hydro and REMO-NH. The advanced models will be constrained by data acquired in dedicated field campaigns (e.g., see above) and will include physical processes not currently considered in (weather) prediction models (e.g., aerosol-cloud-radiation; secondary ice formation; impacts of aerosols and stratospheric ozone). Convective-scale data assimilation tools will be developed to deal with high-resolution models and non-operational measurements during field campaigns. To manage the unprecedented amounts of data from high spatial and temporal resolutions, new strategies, and software tools for data handling and analysis, including artificial intelligence techniques, will be adopted. These model systems will be used for predictions, projections, and analysis of future, present, and past climates (with T2). This WP contributes with M1.8-1, M1.9-1 and D1.8, D1.9 (CTA ESM, CARF REKLIM, NFDI, CARF JL-ExaESM).

Improved predictions from weather to climate scales (KIT, GFZ, AWI). The aim here is to achieve quantifiable improvements regarding different aspects related to the prediction of weather and extremes. The temporal focus ranges from synoptic to climate scales, and the spatial focus from regional to local scales. On short time scales, the aim is to provide better predictions of single events like windstorms, heat- and cold waves, heavy precipitation, floods, droughts (ICON), dust storms and volcanic ash dispersion (ICON-ART). The latter are phenomena not yet covered in standard operational procedures. A strong focus will be on the enhancement of predictions on sub-seasonal scales, and the consideration of clustering (sequences) and compound (multi-risk) events based on regional and global ensemble predictions. On decadal and longer time scales, the focus will be on the quantification of changes in the frequency and intensity of extreme events. The added value of the higher spatial and temporal resolutions, as well as new model components, is quantified, with special attention given to the role of internal variability vs. the anthropogenic signal. Hierarchical and idealized modeling work, such as pseudo-climate change studies at very high resolution will support these developments, e.g., to quantify systematic shifts in cloud properties and radiation in a future climate, different partitioning of warm and cold rain processes, and the enhanced role of diabatic processes for the development of storms. Improved GNSS based atmospheric data sets for Germany (Multi-GNSS, atmospheric slants, and gradients, real-time) are provided for specific impact studies on the forecast improvement of strong precipitation events, in cooperation with DWD. Novel analysis tools will optimize the use of the large datasets efficiently. This WP

[33] *Kottmeier C, Adler B, Kalthoff N, Löhnert U, Görsdorf U. 2019. Integrated vertical profiling. In: Foken (Ed). Handbook of Atmospheric Measurements, Springer, in press, 2019.

contributes with milestones M1.9-2, M1.10-2 and to deliverables D1.9, D1.10 (CARFs REKLIM and HI-CAM, NFDI, CTA Extremes).

Tailored information for users and stakeholders (KIT, HZG). The prediction of weather, and particularly of extreme weather impacts, is of great importance to society in a changing climate. Focusing on highly sensitive regions (e.g., Alpine region, Central Europe, Mediterranean region, Sub-Saharan Africa), the aim is to provide tailored climate information targeting individual socio-economic sectors (energy, insurance) to support climate change adaptation on regional to local scales, e.g., towards improved water- or energy supply management through better-informed predictions. Examples of applications include the development of better prediction of volcanic ash impacts on time scales of a few days with the DWD and the quantification of the costs of climate change to natural hazard risks affecting Central Europe (e.g., windstorm and flood losses) together with insurance companies. This activity is conducted in close exchange with the activities in T4 and integrates the South German Climate Office and CEDIM. This WP contributes to M1.10-3 and D1.10 (CTA Extremes, NFDI, CARF HI-CAM).

Deliverables (D) and Milestones (M)

- **D1.8 (2024):** Documented assessment of convection resolving models (ICON) compared to quality-assured data sets from observational campaigns (KITcube, AIDA, GNSS). **M1.8-1 (2024):** Prototype model systems (based on ICON/ICON-ART) for processes, sub-seasonal, seasonal, decadal predictions and climate projections at the kilometer scale for enhanced predictions of weather, composition and regional climate available. **M1.8-2 (2024):** Series of pilot observational campaigns (MOSES, CrossInn, ScaleX, TeamX Alpine campaigns) on boundary layer exchange processes, clouds and precipitation are conducted including novel commercial microwave links as well as novel GNSS techniques. Quality assured data are available via the ATMO-HUB (part of the Helmholtz data management initiative).
- **D1.9 (2027):** Complete development and provision of an ICON/ICON-ART model for seamless prediction for time scales from weather to climate predictions/projections. **M1.9-1 (2027):** Development of ICON-LAM and ICON-LEM within community efforts of HD(CP)2, CLM, and advancing ICON-ART by expanding its use to climate scales. **M1.9-2 (2027):** Assessing ICON predictive skill for different forecast horizons, in particular, sub-seasonal and decadal, as well as in regionalized high-resolution projections.
- **D1.10 (2027):** Future weather and climate extremes/impact scenarios based on a comprehensive experiment/modeling endeavor. **M1.10-1 (2027):** Series of expanded observational campaigns on processes shaping extreme weather events (convective systems, storms, heavy precipitation). **M1.10-2 (2027):** Assessment of mean changes of weather and weather extremes in past and future climates by a merged statistical and modeling approach. **M1.10-3 (2027):** Establishment of platforms of proven methods in the transfer of tailored information on climate and predictions for users and stakeholders.

Infrastructures and specific resources. KITcube, the advanced integrated atmospheric observation system, is the main infrastructure of the STs. It allows detailed process studies on land surface – boundary layer processes, tropospheric transport, and the evolution of moist and deep convection. Inside Clouds, a KIT investment to develop cutting-edge research platforms, extends KITcube with instrumentation for vertical profiling of turbulent fluxes (FLUXcube), which are crucially missing parameters, as well as new aerosol-measurement instrumentation. It is intended to make KITcube a DFG Core Facility and to provide new access options for researchers beyond KIT, including student education and practical research training.

GFZ operates advanced operational GNSS processing centers based on data from ground networks and radio occultation satellites, complemented by a VLBI analysis facility. Their capabilities will be improved and extended by the application of the GNSS-Reflectometry for innovative and complementary observations over land, sea, and ice (link to T2). Contributions exist to the Global Climate Observing System (GCOS) with ST1.2.

Cooperation partners. Research in ST1.3 contributes strongly to the internationally organized research agendas of WCRP and WWRP. An important link is the WWRP High Impact Weather Project (HIWeather) that promotes research regarding the forecasting of high-impact weather events towards increase resilience against potential disasters. Of similar relevance are the sub-seasonal to seasonal (S2S) project of WWRP/WCRP, as well as the WCRP CORDEX Flagship activities LUCAS and Convection, involving many ST1.3 researchers. On the European level, research is conducted in cooperation with the European Center for Medium-Range Weather Forecasts (ECMWF) and is linked to the COPERNICUS climate service (C3S).

In Germany, meteorological warning management is a statutory duty of DWD and one of its main tasks. DWD and other governmental institutions seek partnerships with academic institutions such as the Helmholtz Centers in ST1.3, filling important science gaps beyond operational services and statutory duties of agencies. Universities and Helmholtz centers cooperate in large project consortia (ClimXtreme, RegIKlim, TR-SFB Waves2Weather); MOSES.

Risks and opportunities of Topic 1. All T1 activities (all Subtopics) are directed at **resolution enhancements** in the dimensions space, time, and processes. They will tackle challenges of implementation for high-performance computing, as well as in data generation and use. This comprises risks, including limitations by capacity or delays due to porting software to new platforms. However, the opportunities of pioneering new observations and modeling at unprecedented resolution, and, in turn, of developing innovative infrastructure and expertise, outweigh these risks.

More specifically, we would like to consider opportunities and risks due to two aspects in T1: our new organizational structure, and our research infrastructure.

Structural. The new organizational structure of T1, with scientists from five Helmholtz Centers collaborating on questions of fundamental nature in the atmospheric and climate sciences, presents the opportunity to benefit from a wide spectrum of expertise and experience. This will likely be most evident in ST1.2, with strong engagement of all five participating Centers. Moreover, recent high-level recruitment (new professorships and young investigator groups) in all Subtopics, leads to an overall strengthening of T1 (compared to ATMO in PoF III): T1 spans more research themes, where we have a 'critical mass' of scientists. This 'critical mass' is indicated by the generation of third-party funded projects as thematic extensions of programmatic research. The ensuing significant addition of expertise from postdocs, graduate scientists and technicians supports a high-end research environment. Example areas include atmospheric dynamics, modeling, and extreme events; aerosol- and cloud physics; middle- and upper atmosphere dynamics and chemistry; land use change and climate interactions; and biogeochemical cycling. Moreover, T1's formative role in existing and planned CARFs/CTAs (see Section E) assures adequate representation of the Topic's research themes across the entire Research Field.

These structural opportunities place us in a highly competitive position in the international research community. However, running programmatic research in a large, geographically and institutionally distributed cluster, with a wide spectrum of specializations, carries the risk of costly coordination efforts, and losing the coherence of the research effort in the Topic. We intend to minimize that risk by our proven communication and knowledge transfer concept (in ATMO, both internally and externally), including regular coordination meetings among the lead scientists, and retreat-type exchange events for Ph.D. students and postdocs. By extending our talent management strategy to postdocs, we strive to ensure continued access to the best junior scientists (especially relevant in view of rapid innovation in data analytics and modeling, including deep learning and artificial intelligence techniques).

With a large volume of externally funded project obligations, there is a risk that these may detract from T1 research objectives and dominate the use of resources. However, also in this respect, we can build on many years of experience and have adopted a policy to apply for external funding only if there is considerable synergy with the PoF research goals.

Observation and Modeling infrastructure. One of the greatest strong-points of our research (see PoF III scientific review) is the close combination of observations and numerical modeling in nearly all aspects of T1. Sections B, C, and E briefly describe the benefit of our joint observation and modeling infrastructure, the related research policy objectives and future perspectives. The above structural opportunities will improve and diversify our access to high-end observational and modeling infrastructure, and foster developments of a concerted 'system of systems' (see Section A). This will enhance the likely impact and relevance of our work.

Research in atmospheric and climate sciences generally depends on the ready availability of hardware and software, for measurements, data mining, and modeling. T1 operates and has access to a remarkable set of observational infrastructure and computer resources, either within the Topic, in collaboration with other Topics in the Program or via external partners (e.g., DWD and DLR). The need to continuously develop and renew this infrastructure is both an opportunity and a risk. We address this risk by staying at the forefront of developments through continual refinement and innovation of sensors and modeling systems, and by comprehensive national and international collaborations.

E) Previous achievements of the contributing centers and infrastructures

Expertise and preliminary work. The scientific achievements of T1 scientists are described in detail in the PoF III Scientific Status Reports of 2017/18. They were evaluated as overall 'outstanding' by the international review panel. In the following, we highlight some of these efforts and recent developments (2017–19) not covered by the Status Reports.

The scientists of **ST1.1 Air Quality** bring together excellence in modeling and observation-based atmospheric chemistry and regional modeling. Large-scale observational and experimental facilities serve to enhance understanding of climate change impacts on air quality, and vice-versa. Previous pioneering findings of unexpectedly high concentrations of the hydroxyl radical (OH) observed in the field,[34] auto-oxidation reactions of biogenic volatile organic compounds,[35] and the effect of mixtures on aerosol formation[36] has stimulated much new research. The IAGOS program provides a powerful reference dataset of water vapor, ozone, and nitrogen oxides for global model evaluation. The GERICS regional modeling team developed a stakeholder decision-making toolkit that integrates physical and socio-economic models and data.

The partners of **ST1.2 Climate Feedbacks** uniquely combine observations, process-oriented simulations, and Earth system modeling to understand changes in atmospheric composition, circulation, and interactions with the land surface that drive regional and global climate change. Pioneering work on the composition of the Asian Tropopause Aerosol Layer (ATAL),[37] ice nucleation studies,[38] reconciliation of ozone loss and assessments of geo-engineering hazards, serves as a solid basis for the new work program. The partners operate a unique set of internationally used infrastructures, including AIDA, IAGOS-CARIBIC, NDACC stations, TERENO-preAlpine,[39] GNSS, and contribute to novel airborne instrumentation (e.g., GLORIA) and satellites (AtmoSat concept, Spatial Heterodyne Spectrometers). Coupled physical and social-dimensions models explore socio-ecological feedbacks in the land-system, synergies, and trade-offs in climate change mitigation and adaptation measures.[40] Highly advanced process-based modeling capacity, including stable isotope approaches,[41] is developed to quantify the role of land ecosystems in the Earth system, regionally and globally.[42] Hydrometeorological observatories and modeling in climate-sensitive regions such as rural West Africa support the human capacity building in developing countries.

In **ST1.3 Future Weather and Extremes,** renowned experts on the development and application of both complex observational and numerical model systems cooperate on three flagship programs, the AIDA chamber, the KITcube, and ICON-ART. The AIDA aerosol and cloud chamber is an unparalleled facility, which actively facilitates collaboration with 35 international research groups, and has led to unique research in the areas of

[34] *Rohrer F, et al. 2017. Nature Geoscience. 7. doi:10.1038/NGEO2199.

[35] *Ehn M, et al. 2017 A large source of low-volatility secondary organic aerosol. Nature. 506(7489):476–479.

[36] *McFiggans G, et al. 2019. Secondary organic aerosol reduced by mixture of atmospheric vapours. Nature. 565:587–593.

[37] *Höpfner M, et al. 2019. Nature Geoscience. accepted.

[38] *Kiselev A, et al. 2017. Active sites in heterogeneous ice nucleation? The example of K-rich feldspars. Science. 355(6323):367–371.

[39] *Kiese R, et al. 2018. The TERENO Pre-Alpine Observatory: Integrating Meteorological, Hydrological, and Biogeochemical Measurements and Modeling. Vadose Zone Journal. 17(1):180060.

[40] *Brown C, et al. 2019. Achievement of Paris climate goals unlikely due to time lags in the land system. Nat Clim Change. 9:203-208.

[41] *Denk TRA, et al. 2019. Constraining N cycling in the ecosystem model LandscapeDNDC with the stable isotope model SIMONE. Ecology. 100(5): e02675.

[42] *Arneth A, et al. 2017. Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed. Nature Geoscience. 10(2):79–84.

ice nucleation and clouds. KITcube is one of the few facilities around the world for integrated observation by state-of-the-art field campaign research and has been widely used in large field campaigns.[43] ICON-ART is a unique seamless composition-weather/climate modeling tool,[44] and a core element of ICON.

The scientific results are **services to the scientific community, politics, and society**. This includes the support of major (>10 years) datasets. Scientists in T1 have a strong track record in **leading major large-scale collaborative measurement campaigns, international research projects**, and **leading contributions to international synthesis** (e.g., WMO Ozone Assessments, SPARC reports, IPCC Special Report on Climate Change and Land, IPCC AR6, IPBES Global Assessment). T1 scientists provide **climate services** with stakeholder-adjusted information on regional/local scales world-wide. Especially notable here are the Climate Service Center (GERICS; HZG) and the Southern German Climate Office at KIT.

Key Strong Points. Our **'whole atmosphere' research approach**, with a close combination of observation and modeling of climatically relevant atmospheric processes, and special attention to the interaction of the atmosphere with its adjacent compartments, is an essential strong point of this Topic. Our research results form the scientific basis for the development of sustainable solutions in response to global change effects on air pollution, weather extremes, water scarcity and ecosystem deterioration (e.g., in the sub-Saharan Africa focal region). Our research infrastructure offers excellent teaching and research training opportunities for students and junior scientists. T1 scientists are directly responsible for two BS/MS degree programs (meteorology and remote sensing) and significantly contribute to a number of other programs.

F) Collaboration and transfer

Research Environment. The scientific work of T1 is embedded in a very competitive and rapidly evolving international research landscape. Climate-related questions are top-level priorities in national research plans, large research organizations, and leading international structures. Therefore, T1 scientists are involved in the principal national and international programs in the relevant fields, often in coordinating positions. Through these activities, T1 gains a wide variety of additional collaborations and competences, which have been significantly developed and expanded in the past Program period (PoF III, 2014–2018).

T1 is particularly active in research programs of the WMO: The World Climate Research Program (WCRP), and the World Weather Research Program (WWRP). T1 is contributing as (coordinating) lead authors to the WMO Ozone Assessments and as coordinating lead authors and lead authors to the reports of the IPCC and IPBES, as well as of WRCP-SPARC. Its research and monitoring stations are substantial contributors to the NDACC (Network for Detection of Atmospheric Composition Change) and Global Atmospheric Watch (GAW) programs. T1 researchers take important roles in the WMO's Research and Development Projects (RDPs) such as in THORPEX (a decadal program for improvement of predictions) as part of WWRP.

Partners. Due to the complex and planetary-scale dimension of the subject, atmospheric and climate research is dependent on international cooperation. Strategic cooperation with selected partners provides an added value not only for research but also for education and knowledge transfer. T1 will foster international research cooperation and **collaboration with outstanding partners** with the following objectives:

- enhanced scientific progress via joint projects,
- major contributions to international strategic networks/programs (IPCC, IPBES, WMO),
- joint operation of infrastructures for use by the wider research community (AIDA, IAGOS, SAPHIR, TERENO, KITcube, WASCAL, JOYCE),
- increase international visibility and attractiveness to the best students and emerging young researchers worldwide (MoUs with University of Leeds and PKU),

[43] *Flamant C, et al. 2018. The Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa Field Campaign: Overview and Research Highlights. Bull Amer Meteorol Soc. January 2018:83–104.

[44] *Schröter J, et al. 2018. ICON-ART 2.1: a flexible tracer framework and its application for composition studies in numerical weather forecasting and climate simulations. Geosci Model Dev. 11(10):4043–4068.

- support of tailored research environment and human capacity building in developing countries,
- output-oriented partnerships with companies (insurances, Bruker Corp.),
- provision of near-real-time emergency information on current disasters and their impacts (via CEDIM[45] with World Bank, UN ReliefWeb),
- economic, cultural and social development with a focus on home-regions of centers (climate services, knowledge transfer, outreach, stakeholder exchange)

In this context, we have identified **key strategic collaborations** with national and international partners that already exist, but will be strengthened in the future, to tackle global challenges in joint long-term projects on a sustainable basis.

Name of strategic partner	Fields of cooperation	Joint efforts + perspectives
German Weather Service (DWD)	**Research** ST1.1/ ST1.2/ ST1.3 [associated partner of ATMO Program since 2013, formal agreement 2019] **Knowledge Transfer** **Talent Management**	Joint projects in weather and composition forecast, decadal climate prediction, ICOS, convective scale data assimilation; climate services Joint model development + implementation
German Aerospace Center (DLR)	**Research** ST1.1/ ST1.2/ ST1.3 [associated partner of ATMO Program 2004–08, since 2013] **Infrastructure**	Joint aircraft campaigns (HALO); middle atmosphere dynamics + greenhouse-gas remote sensing from ground-based platforms (TCCON, CoCCON) and satellites (GOSAT, OCO-2, MERLIN, G3E). Joint model development + implementation
Peking University	**Research** ST1.1 **Knowledge Transfer** **Talent Management** Close collaboration since 2004, MoU since 2009 and extended 2014	Regional air pollution control – Impact in Chinese Air Quality actions; atmospheric measurements 'International Joint Lab on Regional Pollution Control' (IJRC) with PKU (2019), Student and postdoc exchange
UCAR / NCAR	**Research** ST1.2 **Infrastructure** MoU since 2012, extended 2017 until 2023	Joint aircraft campaigns; modeling of land use change impacts on ecosystems and climate; T1 scientists are sole European partners of new NCAR Antarctic campaign SOCRATES
University of Leeds	**Research** ST1.2/ST1.3 **Talent Management/Education** Long-standing collaboration, MoU signed 2019	Aerosol-cloud processes; Africa research, major field experiments Exchange of students, postgraduates and staff (Summer schools on Ph.D. level, Erasmus)
Consultative Group on International Agricultural Research (CGIAR) Institutes	**Research** ST1.2 **Talent Management/Education** Long-term co-operation since 2000 (IRRI, ILRI)	Observations and modeling of GHG effectiveness for agricultural management practices and land use change; joint projects and operation of research laboratories Exchange of scientists (≈20 years); joint support of Ph.D. students

[45] Center of Disaster Management: forensic disaster analyses and risk reduction technology.

The most significant external contributions to T1 are provided by the long-term associated partners, the Deutsches Luft- und Raumfahrtzentrum DLR-IPA (Institutes for Atmospheric Physics, and Solar-Terrestrial Physics), and the Deutscher Wetterdienst DWD (Business Areas 'Research and Development' and 'Climate and Environment').

Cross-Cutting Activities and Alliances. T1 contributes to and benefits from several cross-topic activities within RF E&E (CTAs) and in collaboration with other Research Fields (CARFs). Subtopic specific CARFs/CTAs are described in the respective sections.

For T1, **REKLIM** will play a critical role in bringing together research activities on regional climate change across Topics, as well as on analyzing extreme events in various contexts, including the societal context. T1 will also benefit from well-established knowledge transfer activities in REKLIM.

Earth system modeling activities form part of the strategic development in T1 and contribute to the national strategy. Technical work on the coupling of subsystems, with a particular focus on composition (water – in all its phases, aerosols, chemistry) will be performed and will be available for external users. A seamless modeling approach (across temporal and spatial scales) will be pursued, and coordinated numerical experiments (including frontier simulations) with standardized model configurations will be performed. Part of this work can also act as a 'drivers' contribution to **HI-CAM**.

A close link to the **RF Information** exists and will be developed further, for example, in the areas of using tiered storage hierarchies, general scalability, workflows, use of new hardware and data compression. Our ability to perform cutting-edge simulations will directly benefit from many of those activities. Data science activities will play a central role in supporting new scientific discoveries and will form an important part of our educational activities. Here, the 'Helmholtz Inkubator' approach has provided new impulses, for example, the Helmholtz Analytics Framework (HAF) and a number of 'designed platforms' for example, Artificial Intelligence (AI) and metadata. As part of the digitalization strategy – of the RF and Helmholtz as a whole – T1 actively pursues the development of an integrated data hub structure (**ATMO-HUB** – with compatible counterparts MARE and TERRA in other Topics). Furthermore, the CARF **JL-ExaESM** will support HPC usage for Earth system modeling. In conjunction with the CTA **DE** and the general data science activities, comprehensive campaign data archives will be built. Data will be available for numerous applications, including model validation and development.

Observational capabilities and capacities are coordinated in **TERENO** and boosted by **MOSES**. Here, event chains – and in particular hydrological extremes – will be measured and analyzed in unprecedented detailed with the aim of improving forecasts and allowing for efficient early warning systems.

CTA **Extremes** explores fundamental scientific challenges of atmospheric-, geospheric-, geological-, and oceanic extreme events that pose a potential threat to societies, their assets, and the environment (close links to T2, T3, T5-T7).

The CARF **Resilient Urban Spaces** will combine expertise and boost research on interactions of global change with cities and urban-rural regions in three modules: hazards and urban risks; healthy life in a smart city; and urban climate and environment – with strong connection to T4-T8, RF Aeronautics, Space and Transport, and RF Health.

Earth Observation (EO) and Remote Sensing (RS) play a central role for T1 as a provider and user of EO and RS data. The **RF Aerospace, Space and Transport** (DLR) is an important partner in this area. We will pay special attention to the 'exploration' of unprecedented atmospheric limb imaging methods as well as innovative lidar, Synthetic Aperture Radar (SAR) and hyperspectral techniques. Existing and future satellite (and additional remote sensing) data will be used to monitor the state of our planet and to diagnose trends and variability. In addition, data products will be used to validate and improve models.

Transfer and contribution to SynCom. Over the past decades, knowledge and technology transfer (KTT) has become a central part of scientific endeavor. In T1, **five dimensions of transfer** are prioritized. These KTT contributions of T1 to the entire Program correspond to the SynCom goals, themes and tools:

- Collaboration and transfer across Topics and RFs in the **CCA framework** (and SynCom)
- Contribution to/integration in **international scientific programs and networks**
- Discourse with **public stakeholders** via an objective research communication platform

- **Science-policy consulting** for governments and government-agencies at all levels
- Direct **implementation of research results in joint projects** with, e.g., DWD or industry

The basis of science and technology transfer supplied by T1 is the scientific expertise developed and achieved through research in its Subtopics as a contribution to SynCom.

A **primary channel of science transfer** in T1 is through the teaching of university degree programs. Beyond that, T1 will further develop science and technology transfer concepts to serve legislative and government institutions at all levels, economy, the public, and the wider research and public services communities, as a basis for science-based decision-making. This will be achieved most prominently through the active participation in international assessments and reports (including IPCC, IPBES, TOAR, WMO, UNECE-HTAP, and LRTAP). On the local and regional level, science transfer will take place via discourse with politicians and public stakeholder groups (in Germany and internationally) through cross-cutting initiatives (REKLIM, HI-CAM), modules in the GERICS adaptation toolkit for cities (ST1.1), tailored climate service for specific regional adaptation measures in, e.g., agriculture, forestry, or city planning (ST1.2), and on natural risks by CEDIM and the Regional Helmholtz Climate Offices (ST1.3).

Considerable **technology transfer** in T1 will be achieved by the further development of instrumentation and software tools for data analysis and modeling, and making these accessible to stakeholder groups, including the insurance industry, weather and disaster management services, government agencies, universities, and research institutions worldwide. Where appropriate, intellectual property rights are assured through patents and licenses.

Knowledge transfer to the public about impacts of the atmosphere in global change is achieved through public lectures, tutorials with schools, stakeholder dialogues, web information systems[46] and information material coordinated through the Regional Helmholtz Climate Offices, REKLIM, and SynCom. In a step towards research for and with society, T1 will implement innovative Citizen Science projects to enhance public and scientific awareness of challenges associated with the atmosphere in global change, such as within the large BMBF-funded projects MIKLIP, ClimXtreme, and RegIKlim, where T1 researchers have co-leading roles.

T1 is a pioneer in providing open access data (e.g., IAGOS data have been provided free of charge since 1994 and TERENO data since 2010). It will serve the wider research community through further developing **concepts of data services and management complying with FAIR principles (ENVRI-FAIR),** in particular with the so-called **ATMO-HUB** as part of a data management concept for the whole Program. FAIR data enhances the efficiency and productivity of researchers, supports innovation, and enables data- and knowledge-based decision-making.

Capacity building is mainly driven through the institutionalized operation of international and joint laboratories, such as the International Joint Laboratory on Atmospheric Chemistry (FZJ, PKU), the Helmholtz international laboratory AeroHEALTH (HMGU, FZJ, Weizmann Institute), the WASCAL Competence Centre in Burkina Faso (KIT), the International Rice Research Institute (IRRI) in the Philippines (KIT) and the International Livestock Research Institute (ILRI) in Kenya (KIT).

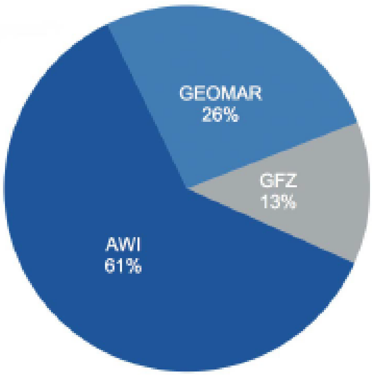
[46] As examples, see the online NO_x calculator (see https://stickoxid-rechner.de/), or a tool for farmers to minimize GHG emissions and nitrate leaching in grassland management (see https://dss.susalps.de/demo/).

Executive Summary

- T1 addresses three research areas of societal relevance for the Atmosphere in Global Change: i) Air Quality, ii) Climate Feedbacks, and iii) Future Weather and Extremes. We strive to develop scale-crossing observational and modeling solutions for improved atmospheric predictions and regional climate projections at unprecedented resolution. With our 'whole atmosphere' approach we aim to observe, understand and predict atmospheric phenomena and process chains from drivers to climate change impacts throughout all levels of the atmosphere, and especially in their interaction and feedbacks with the adjacent compartments (land surface, biosphere, cryosphere, ocean, and near-Earth space).
- We will: i) determine consequences of global change for sources, sinks and transformation processes that affect air quality and atmospheric composition (incl. greenhouse gases), as well as their impacts on health, economy, and quality of life, ii) explore and quantify the feedback-web between physical, chemical, biological, and socio-economic processes and mechanisms in the Earth system, iii) assess extreme weather events in terms of their predictability and trends in frequency and magnitude with climate change, iv) provide stakeholder-tailored climate services
- With scientists from five Helmholtz centers collaborating in T1, we can build on a unique portfolio of competence and expertise to address global change processes throughout the whole atmosphere, including its interaction with the adjacent Earth system compartments. Our unique combination of infrastructures (observational and modeling) fosters international co-operation and provides cutting-edge research and research-training options.

Topic 2: Ocean and Cryosphere in Climate

Spokespersons: Thomas Jung, AWI; Deputy: Katja Matthes, GEOMAR



Topic 2 will advance the understanding of past, present and future changes of the climate system from an ocean and cryosphere perspective by closing critical knowledge gaps related to warming climates, variability and extremes as well as sea level change for the benefit of society. The new knowledge on important parameters such as land and sea ice, sea level and ocean current systems along with advanced research methodologies will enhance prognostic capacities from the poles to the tropics and from daily to millennial time scales. A specific focus is on the improvement of regional estimates of changes for the years 2030, 2050 and 2100, and pathways into a 1.5°C, 2°C and 4°C warmer world. Thereby, Topic 2 will provide actionable knowledge for a wide range of climate-ocean-cryosphere services and inform decision-makers on current and plausible future climate states; it will also serve as a basis to develop mitigation and adaptation strategies.

A) Scope and challenge of the Topic

Research subject. The ocean and cryosphere are two central components of the Earth system. The ocean covers 70% of the Earth's surface and acts as a buffer of the climate system, balancing extreme temperature fluctuations and redistributing heat between tropical and polar latitudes. Since the industrial revolution, the ocean has absorbed about 90% of the heat trapped in the climate system in response to increasing atmospheric greenhouse gas concentrations and 30% of the CO_2 that humans have released into the atmosphere. Sea ice covers vast areas of the polar oceans and modulates the energy balance between the surface and the atmosphere. Ice sheets are the greatest potential source of freshwater, corresponding to about 70 m of sea level equivalent. The effects of anthropogenic climate change have a clear, measurable impact on the ocean and the cryosphere. The ocean is warming and becoming more acidic with implications for critical ecosystem services; sea level is rising, partly fueled by increasing melt rates of ice sheets and shelves; and sea ice is retreating and the circulation is changing with substantial impacts on global and regional climate.

Topic 2 (T2) explores the role of the ocean and the cryosphere in climate across a wide range of time scales from days to millennia and from the past and present into the future. Special emphasis will be placed on evaluating the consequences of possible future climates in a warmer world, with a focus on changes in regional sea level, ocean current systems, sea ice and ice sheets. Efforts will focus on unraveling the mechanisms controlling regional modes of climate variability and extreme events. T2 will develop and apply advanced research methodologies including novel in situ and remote sensing observing systems, new paleo proxies, innovative analytics, advanced theory and numerical models as well as innovative data science concepts. T2 will provide improved estimates of uncertainty and prognostic capacity for stakeholder-relevant parameters.

Explanation and justification of research. Our planet is undergoing an unprecedented and rapid system change with profound implications for society as recognized by the Global Risks Report 2019 that ranks climate-related environmental risks amongst the top five global risks for society (GRRT 201947). The ocean and cryosphere play critical roles in this rapid transformation. T2 will explore the mechanisms by which the ocean and the cryosphere participate in modes of natural climate variability, and their response to anthropogenic change. T2 will address the consequences of meeting the targets of a 1.5°C and 2°C global temperature rise (Paris Agreement) for 2030, 2050, 2100 and beyond relative to pre-industrial times, and also investigate possible 'hothouse'-scenarios of 4°C global warming, taking into consideration periods with similar temperatures in the past. The relevance of the ocean and cryosphere for climate change has been recognized by the Intergovernmental Panel on Climate Change (IPCC) through the Special IPCC Report on the Ocean and Cryosphere in a Changing Climate (SROCC48), to which we contribute substantially with research and experts. The strategy of T2 also is fully in line with the new WCRP Strategic Plan for the period 2019–2028[49]: T2 will contribute new fundamental scientific understanding to improve predictions of short-term and long-term responses of the climate system, to transfer data and knowledge of climate science to society, and to address SDGs 13 (Climate Action) and 14 (Life Below Water).

Strategic guidelines (FoPoZ). T2 will investigate the role of the ocean and cryosphere in climate variability and change; from the past to the present, and into the future. Based on innovative research methodology and technology, T2 directly addresses the following specific strategic goals: i) Provision of the scientific underpinning for more reliable projections through improved process understanding, for example employing data from the MOSAiC experiment,[50] and assessment of past warming climates, ii) Better assessment of the consequences of a 1.5°C vs 2°C warmer world (relative to pre-industrial times) in 2030, 2050 and 2100 and of possible 'hothouse scenarios', iii) Improved understanding of natural climate variability and extreme events, and better ability of numerical models to represent these, iv) Closing critical knowledge gaps of sea level rise and development of advanced prognostic capacity at the regional scale by developing sustained monitoring capabilities and improved Earth system models. The research goals of T2 are consistent with those of MARE:N, the BMBF strategic program for the ocean, by directly addressing the themes 'global change and climate', 'matter and energy fluxes', and 'environmental risks' including 'extreme events'. 'Future changes in ecosystem functioning and biodiversity' are addressed through strategic collaborations with T4 and T6 (marine) and T5 (terrestrial). T2 also contributes to GEO:N, the BMBF strategic program for the solid Earth, for example, by carrying out gravity field observations from local to global scales and by providing high-resolution paleoclimate data.

Function and contribution of the Topic within the Program. T2 contributes to the Program by adding strong expertise on the ocean and cryosphere along with their role in climate. Through close collaboration with atmospheric scientists in T1, we will address a wide spectrum of extreme events, including storms and oceanic heatwaves, as well as abrupt shifts in ocean circulation and ice sheet dynamics from the past to the future. Collaboration with coastal research in T4 will enable a comprehensive assessment of sea level rise, from sources in the polar regions to local impacts in coastal regions where sea level rise is felt most strongly. Together with T4, T2 will also contribute to the determination of element and matter fluxes in the coastal transition zones, across the shelves and to the open oceans. Collaboration with T5 will enable addressing the impacts of climate change and extreme events on Earth surface systems, including permafrost environments. Finally, close collaboration with biogeochemical ocean sciences (T6) will enable evaluating how climate variability and change affect carbon fluxes and life in the ocean and lead to potential tipping points in the Earth system. T2 plays a leading role in strengthening and coordinating different Earth system modeling activities[51] within the Helmholtz Association as well as in shaping a national Earth system modeling strategy. Furthermore, T2 develops and provides innovative methodologies, including cutting-edge modular monitoring, analytical facilities, and innovative data science concepts, thus exploiting and strongly contributing to the field of digitalization.

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[47] 14th Global Risk Report 2019. World Economic Forum Davos; https://www.weforum.org/reports/the-global-risks-report-2019.

[48] See https://www.ipcc.ch/site/assets/uploads/2018/04/Decision_Outline_SR_Oceans.pdf, update released in Sep 2019.

[49] See https://www.wcrp-climate.org/images/documents/WCRP_Strategic_Plan_2019/WCRP-Strategic-Plan-2019-2028-FINAL-c.pdf.

[50] Multidisciplinary Drifting Observatory of the Study of Arctic Climate, https://www.mosaic-expedition.org.

[51] Modeling activities in T2 are primarily based on systems employed at AWI (e.g., FESOM, see http://fesom.de), GEOMAR (FOCI –Flexible Ocean Climate Infrastructure) and GFZ (viscoelastic lithosphere and mantle model VILMA). Work has started towards employing a common modeling infrastructure using ESM-Tools (see http://esm-tools.net).

Highlights. MOSAiC (Multidisciplinary Drifting Observatory of the Study of Arctic Climate): The flagship project MOSAiC will provide an unprecedented dataset of the functioning of the Arctic climate system over a full annual cycle, including the poorly-observed winter season. The data gained from the observational network of MOSAiC will allow improving our understanding, and thus existing parametrizations, of processes governing Arctic Amplification and the assessment of a new generation of high-resolution weather and climate models (down to 1 km resolution) explicitly resolving small-scale processes (e.g., those related to sea ice leads) for advanced predictions and projections in the Arctic and beyond. MOSAiC data will be exploited jointly with T1 and T6.

Upwelling in a changing world: Oceanic upwelling systems in the tropics and mid-latitudes, mainly located at eastern ocean boundaries, host the most productive ecosystems in the world and are fundamentally important for fisheries and food security (T6). Upwelling systems are subject to large natural variability on time scales from weeks (wind-driven upwelling events) to decades (in association with different climate modes), to century-long trends as documented in sedimentary records. Global warming impacts upwelling systems but the magnitude and extremes of these impacts, for example on the occurrence of hypoxia, are largely unknown, also hampered by the poor representation of small-scale near-coastal processes in current numerical ocean system models. T2 will develop and design coastal upwelling studies off Northwest Africa (relying on established collaboration with Cape Verde, Mauritania, and Senegal, as well as in the frame of the pan-Atlantic ocean observing system and with other international partners), focusing on ocean system dynamics and will improve the representation of these processes in operational upwelling forecasts (Copernicus Marine Environment Monitoring Service, CMEMS).

Challenging numerical models in their ability to represent the full range of natural climate variability: Knowing the magnitude of natural climate variability is important for the detection and attribution of anthropogenic climate change and the projection of future climate changes. Research in PoF III has revealed striking and yet unexplained discrepancies between regional sea surface temperature variability in state-of-the-art climate models and paleo-reconstructions on decadal and longer time scales, suggesting that climate models underestimate the magnitude of internal variability as well as the climate response to natural forcings. T2 will bring together new long-term instrumental observations, high-resolution paleo-reconstructions, climate dynamics and advanced climate modeling to rigorously contrast the climate models' natural variability with observations over a broad range of time scales. By better representing natural climate variability, this work will improve future climate projections needed for suitable adaptation strategies, in particular on a regional scale.

Realization of the next-generation mass change mission (MCM): A next-generation MCM shall be realized by another US-German cooperation and extend the GRACE/GRACE-FO observation period to obtain reliable statistics and to significantly increase the spatio-temporal resolution of measurements (see Ch. 1.4.2[52]). The MCM scheduled for launch in 2027 will provide ground-breaking data, particularly for research covered by T2 and T5, that will allow us to, for example, disentangle the effect of global warming and climate modes on sea level, monitor ice sheet mass balances and processes driving ocean circulation, start resolving individual drainage basins of ice sheets, and realize the operational use of satellite gravity products for near real-time applications, such as flood alerting or groundwater monitoring.

B) Main research and structural objectives

Research Objectives.

- **Objective 1:** Provide the scientific foundation for improved climate projections through better understanding of key ocean and cryosphere processes governing past and current warming climates.
- **Objective 2:** Enable a major advance in our ability to observe, understand, simulate and predict natural climate variability and extreme events along with their impacts from an ocean and cryosphere perspective.

[52] With MCM and MUSE (Marine Umweltrobotik und -Sensorik für nachhaltige Erforschung und Management der Küsten, Meere und Polarregionen), T2 supports two strategic investments. MUSE is proposed to develop and implement next generation marine robotics and sensor systems with the aim to facilitate science for upcoming challenges arising from changing global oceans under intensifying human pressures.

- **Objective 3:** Improve the quantification of recent and future regional sea level rise by addressing critical knowledge gaps related to processes in the ocean, cryosphere, and the geosphere as well as their interactions.
- **Objective 4:** Provide advanced estimates of the near future climate in 2030, 2050, 2100 and beyond as a consequence of 1.5 °C, 2 °C and 4 °C global temperature increases with emphasis on changes related to the ocean and cryosphere.
- **Objective 5:** Develop, test and apply new, innovative research methods in the fields of observation, remote sensing, paleo-reconstructions and proxy development, climate modeling and data science that will result in a leap forward in our ability to carry out scientific investigations at an internationally leading level and to provide actionable knowledge to decision-makers and society.

Structural Objectives.

- **Objective 6:** Strengthen the collaboration between AWI, GEOMAR and GFZ within T2 and with interdisciplinary research teams within the Program (in particular T1, T4, T6), as well as partners from the Max-Planck and Leibniz Societies and German universities.
- **Objective 7:** Advance science by further integrating observations, paleo-reconstructions and modeling across a wide range of spatial and temporal scales.
- **Objective 8:** Establish T2 as a major contributor to international climate research (e.g., WCRP) with a focus on the role of the ocean and cryosphere in a warming climate, by leading international initiatives and activities.
- **Objective 9:** Establish the development of advanced research methodologies, such as autonomous ocean and cryosphere observation as well as high-resolution modeling, as an integral part of the overall research agenda.

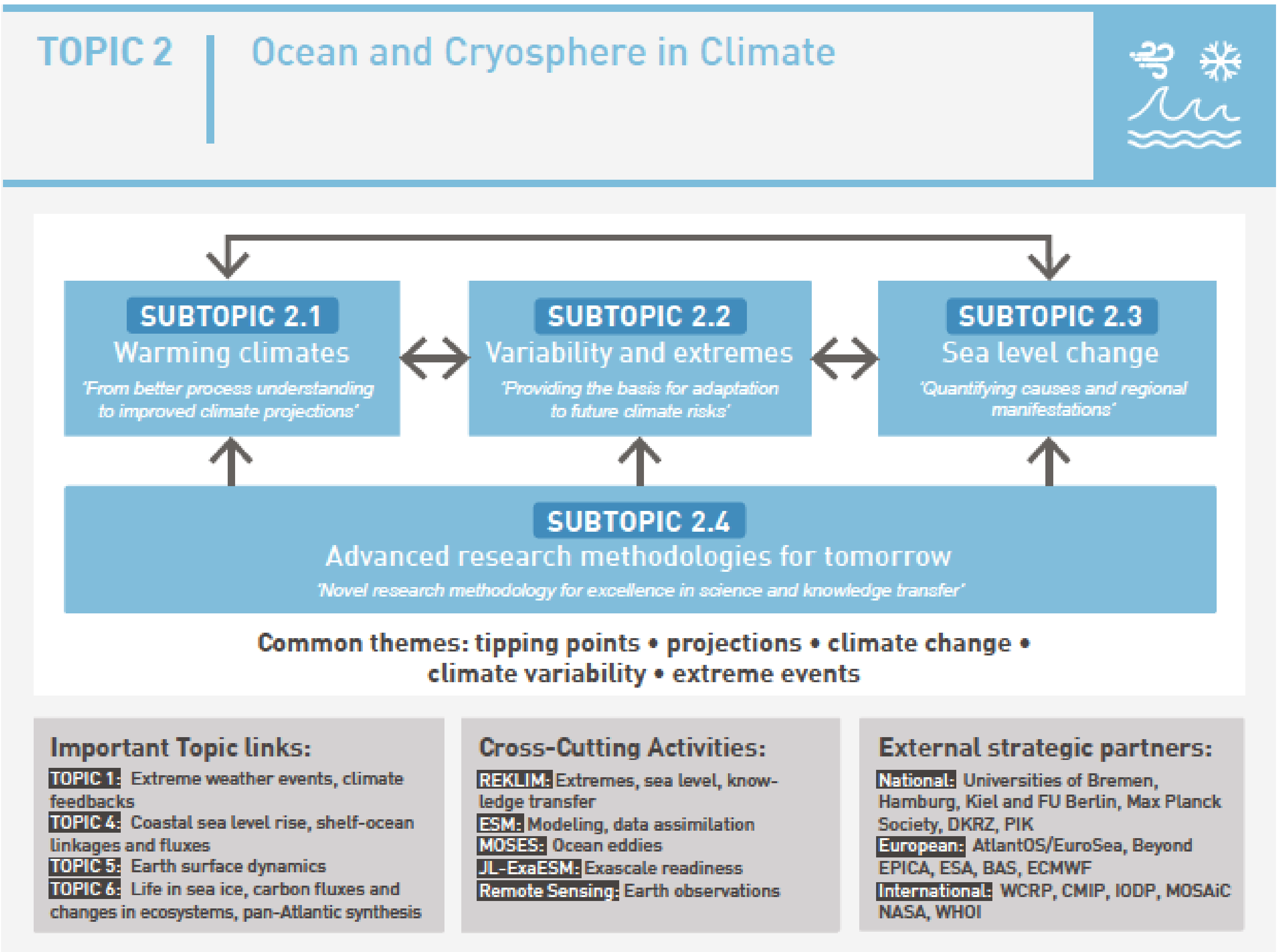


Fig. 2.1: Graphical scheme of T2 with its four Subtopics along with critical links to other Topics, important Cross-Cutting Activities and selected strategic partners.

- **Objective 10:** Strengthen outcome-oriented research and knowledge transfer activities with an emphasis on sea ice, ocean circulation, sea level rise and extreme events, in response to societal needs in informing climate mitigation and adaptation measures.

C) Structure of the Topic and motivation of Subtopics

Introduction of Subtopics. T2 concentrates on four different Subtopics (Fig. 2.2).

Subtopic 2.1 'Warming Climates' will determine the causes of a warming climate and its consequences for the mean state of the global and regional distribution of temperature, sea ice extent, ocean circulation and carbon reservoirs, and their relationships and driving factors from the past to the present and into the future. It has a strong focus on long-term monitoring and process understanding and will include comparison of present-day conditions to past warming climates, their drivers and consequences for marine and terrestrial carbon sources and sinks, and their transitions and tipping points. One ultimate goal is the development of improved climate models, which will increase the reliability of regional-scale projections of future climate for various anthropogenic warming scenarios.

Subtopic 2.2 'Variability and extremes' will focus on natural climate variability and extreme events and their changes under global warming across a wide range of time scales. Integration of (paleo) observations, dedicated observational campaigns and model development activities will enable us to close the knowledge gaps on natural climate variability, thereby increasing confidence in the full range of possible future climate change projections and probabilities of climate extremes to better inform decision-makers. ST2.2 will also improve predictive capabilities on daily to decadal time scales and will consider the driving factors of extreme cryospheric and oceanic events, their atmospheric and oceanic triggers, and consequences.

Subtopic 2.3 'Sea level change' will concentrate on present-day and future sea level rise with a specific focus on polar sources and regional changes. By combining novel monitoring, reconstruction, modeling and projection capabilities, individual causes of sea level change will be quantified. In particular, processes, which are still poorly understood and not well represented in existing modeling systems, will be considered, such as dynamics of ocean-ice sheet systems, self-gravitation or interactions with the solid Earth. The activities will guide the development of an advanced Earth system model with interactive ice sheets capable of realistically simulating ice-shelf-ocean-geosphere interactions and thus sea level changes. ST2.3 will also provide advanced monitoring capabilities, sea level change observations and projections with reduced structural uncertainty.

Subtopic 2.4 'Advanced research methodology for tomorrow' will develop, test and provide cutting-edge tools and methods to enable excellence and international leadership in observational campaigns, remote sensing, high resolution reconstruction of past ocean and climate states, Earth system modeling, as well as new data science applications. This Subtopic provides the important methodological underpinning foundation for research in STs 2.1 to 2.3.

Contributions of the Centers to the Topic. AWI, GEOMAR and GFZ will be involved in all four Subtopics. In the following, key contributions of each of the centers to the different Subtopics will be briefly described. **AWI** will contribute to ST2.1 through long-term monitoring activities in the Arctic and Antarctic (e.g., sea ice), the improvement of process understanding through field campaigns (e.g., MOSAiC) as well as paleoclimate studies (e.g., IODP, Beyond EPICA-Oldest Ice (BE-OI)) and modeling. AWI will also contribute with its expertise in model development (e.g., employing unstructured mesh methods) and in carrying out community experiments (CMIP). In ST2.2, AWI will investigate teleconnections, especially in terms of polar-mid-latitude linkages and their role in extreme events. In order to put these extreme events into a long-term context, AWI will also contribute to the theme 'paleo-weather' and to advanced reconstructions of natural variability from (paleo) observations, to investigate the relation of extreme events, variability and mean state and to challenge the ability of climate models in simulating these variations. Furthermore, research is directed towards developing advanced predictive capabilities on the time scales ranging from days to seasons. In ST2.3, AWI will contribute by combining observational capacity of ice sheet-ocean systems and their dynamics deployed in strategic key regions with dedicated remote sensing and modeling efforts to provide in-depth understanding of the polar sources of sea level rise. AWI's contribution to developing advanced research methodology in ST2.4 comprises in situ observations, remote sensing, paleoclimate proxies, modeling and data science. **GEOMAR**'s contributions to ST2.1 are key elements of the pan-Atlantic observing system enabling long-term monitoring of the AMOC and tropical variability. GEOMAR will also provide strong expertise in the observation, simulation and analysis of major ocean currents, their variability and changes under warmer climates with high-resolution (eddy-resolving) ocean and climate modeling, as well as dedicated paleo-oceanographic investigations. In ST2.2, GEOMAR's research focuses on tropical ocean dynamics and the impact of external forcings on internal modes of climate variability. This includes the design of dedicated field campaigns in Atlantic upwelling systems, nested ocean-climate modeling approaches, and research on tropical high latitude oceanic and atmospheric teleconnections, regional climate modes, extreme events such as low-oxygen ocean eddies, as well as on decadal variability and predictability. To ST2.3, GEOMAR will contribute investigations of changing oceanic and atmospheric circulation and the propagation of open ocean sea level signals into shelf and coastal regions. To ST2.4, GEOMAR will add new developments in modeling, paleo proxies, autonomous measurements, and innovative data science, such as the Helmholtz School for Marine Data Science (MarDATA). **GFZ** will contribute to ST2.1 and ST2.2 with reconstructing past climate states and weather extremes by developing novel paleo proxy data and precise dating of seasonally resolved non-marine sediment records. With its internationally recognized expertise in the operation and analysis of geodetic observation systems (GFZ is a principal partner of the gravity space mission GRACE-FO) GFZ will provide the observational database for the quantification of global to regional sea level change to be carried out in ST2.3. By coupling a three-dimensional Solid Earth model to an Earth system model and contributing to the development of advanced data assimilation capacity and interactive data exploration tools, GFZ will complement the activities of the partners in strategically relevant areas. It will advance not only the envisaged separation of causes of sea level change in ST2.3, but also the methodological developments in ST2.4. Important contributions by GFZ also include the generation of a highly precise terrestrial reference frame as well as the development of new geodetic monitoring systems for optimized long-term observations of oceanic and cryospheric processes.

D) Subtopics

Subtopic 2.1 Warming climates

Martin Frank, GEOMAR; Christian Haas, AWI

Scope and challenges. The goal of this Subtopic is to better constrain the processes controlling climatic changes in a warming world, with a focus on the ocean and cryosphere, and to transfer this knowledge into better models for advanced projections. Applying novel analytical and instrumental techniques (ST2.4), our research will be based on analyses of past, present and future changes from the polar to the tropical regions and the linkages between them.

The Arctic is one of the most rapidly-changing regions on Earth, with recent sea ice decline being a sentinel of anthropogenic climate change. The observed retreat occurs more than twice as fast as simulated by current climate models, suggesting that critical feedbacks are not well represented in models[53] but are key for improved projections. In contrast to existing climate change projections, the Antarctic sea ice extent has not yet declined significantly. It has, however, become substantially more dynamic in recent years and clear minima in sea ice extent have been observed very recently. To better understand the drivers of present sea ice distribution and to increase confidence in future predictions, we will study the Arctic and Antarctic in a system approach considering processes on time scales from hours to millennia and from local to global scales.

The variability of the meridional overturning circulation in the Atlantic, Southern Ocean, and North Pacific and its impacts during warming climates are not well understood. Global heat exchange, nutrient transfer to and

[53] Some of this discrepancy might also be due to natural variability affecting the observational record. Natural variability will be addressed in ST2.2.

productivity at low latitude upwelling areas, carbon uptake and storage in the (deep) ocean, and oxygen loss in globally warming ocean waters (with T6), depend on short- and long-term changes in the formation and export of water masses from high latitude areas and their tipping points, which will be a focus of ST2.1. Regional challenges will be the detection and quantification of current and future trends of the Atlantic Meridional Overturning Circulation (AMOC) and its complex connections to the polar regions and the Indian Ocean, as well as the Gulf Stream system and its impact on European climate.

To better define natural changes of the mean state of the ocean and cryosphere, we will reconstruct regional and global conditions prevailing during past warming climates with temperature ranges comparable to those predicted for the near future such as the last interglacial (Eemian), the mid-Pliocene and the mid-Miocene periods, taking into account geophysical and tectonic boundary conditions, and apply these to investigate thresholds and disentangle natural and anthropogenic climate changes. The paleo records, along with modeling studies allow the evaluation of the system on its way into and within warmer states, which is not accessible through the instrumental record of the past 150 years.

Main objectives. A key objective of this Subtopic is to achieve an improved understanding of the causes and consequences of the 20th- and early 21st-century global and regional anthropogenically-induced warming and its interplay with the natural variability of the climate system from an ocean and cryosphere perspective, and to turn this knowledge into improved climate change projections, in particular in the polar regions. The dedicated investigation of past warming climates will provide unique ways of evaluating the sensitivity of the Earth system under variable boundary conditions and to define its tipping points and deviations from the mean state beyond the presently prevailing range of climates documented by the instrumental record. We will release comprehensive data sets of key climate variables including challenging autonomous and remote sensing-based winter observations from remote polar regions (MOSAiC) and will ensure the transfer of the new knowledge to policymakers and society at large.

Work program. Past, ongoing and future Arctic and Antarctic climate change. We will investigate critical processes and feedbacks controlling changes in the Arctic and Antarctic, which have shown fundamentally different behavior during the last four decades. Emphasis will be placed on key mechanisms of rapid Arctic sea ice decline and Arctic Amplification. These include processes affecting ocean-sea ice, atmosphere-sea ice and ocean-atmosphere heat fluxes including clouds, vertical radiation, momentum transfer, and ocean mixed layer-halocline coupling, two-way linkages between the Arctic and the mid-latitudes involving atmospheric and oceanic processes, and processes of ice melt and ice edge dynamics in the marginal ice zone.

In Antarctica, our research will contribute to explaining the lack of observed sea ice decline over the whole satellite era vs recently observed sea ice minima. Emphasis will be on the role of ocean eddies, ice shelf and

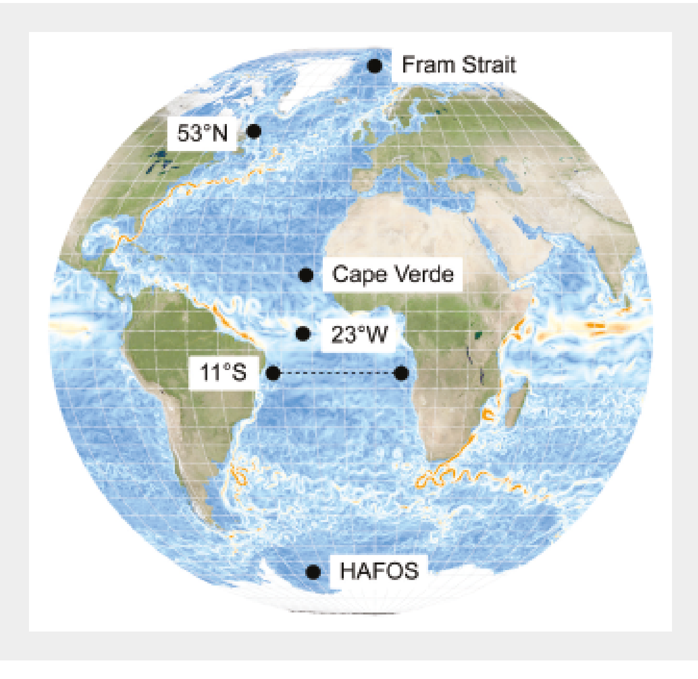


Fig. 2.3: GEOMAR and AWI contributions to the pan-Atlantic observing system. Shown are surface currents from a global high-resolution ocean-only simulation (NEMO-ORCA12) together with locations of long-term ocean observatories in the Atlantic.

sea ice melt, stratosphere-troposphere coupling, atmospheric and oceanic circulation, as well as changes in the Antarctic freshwater balance and bottom water formation.

Our research is based on field campaigns, long-term observations, paleo-reconstructions and modeling. In the Arctic, the MOSAiC campaign will provide the observational basis complemented by campaigns in the central Arctic Ocean and in the region of warm water inflow into the Arctic Ocean via the Fram Strait. In Antarctica, our regional observational focus will be on the Weddell Sea and its linkages to the Antarctic Circumpolar Current (ACC). Field studies will be complemented by application of remote sensing and in situ autonomous observing systems, which will provide the basis for improved parameterizations and the evaluation of high-resolution models. By combining observations and projections with coupled models, ST2.1 will assess the evolution of the Arctic and Antarctic climate system in the 21st century and its impact on the carbon cycle and (polar) ecosystems (with T6).

- **D2.1 (2025):** Comprehensive assessment of the drivers and consequences of polar climate change (together with T6) and specific recommendations for model improvements. **M2.1-1 (2022):** ATWAICE expedition on boundary current-marginal ice zone dynamics and sea ice melt processes north of Svalbard. **M2.1-2 (2024):** Assessment of the role of heat and salt inflow ('Atlantification') into the Arctic Ocean in sea ice decline.
- **D2.2 (2025):** Advanced projections ('CMIP6-Interim') of Arctic and Antarctic climate change based on the AWI climate model. **M2.2-1 (2022):** Improved representation of atmospheric, ocean and sea ice processes (link to ST1.2) in the AWI climate model exploiting MOSAiC data.
- **D2.3 (2027):** Fit-for-purpose observing system with freely available data including key in situ, airborne, and satellite observations. **M2.3-1 (2022):** Delivery of MOSAiC data of the atmosphere-ocean-sea ice system. **M2.3-2 (2023, 2024, 2026):** ArcWatch cruises and airborne campaigns, and remote sensing in the Central Arctic Ocean. **M2.3-3 (2024):** Continued development and expansion of the Hybrid Antarctic Float Observing System (HAFOS) in the Weddell Sea.

Stability of the AMOC. The AMOC exerts a strong control on Northern Hemisphere climate through the Gulf Stream system and on the ocean's ability to take up heat and trace gases such as CO_2 and to store them at depth. The AMOC has been subject to natural changes and trends and is currently at risk of a major slowdown or even collapse due to anthropogenic forcing resulting in atmospheric and oceanic warming and feedbacks from Greenland[54] and Antarctic ice sheet melting. Detecting anthropogenic signals in AMOC strength based on ocean observations is challenging but essential for adaptation and mitigation actions.

Major coordinated observational programs operated by GEOMAR and AWI at key sites in the Atlantic Ocean including the Arctic Ocean and Weddell Sea will now be brought together under one Topic (Fig. 2.3). In collaboration with different international programs and partners the first continuous pan-Atlantic time series of AMOC variability of the past up to ≈20 years have now been achieved, which will be continued with highest priority (link to T6).

To better explore the mechanisms and better predict present and future AMOC strength, we will apply a hierarchy of numerical models focusing on key processes of the AMOC and its ocean heat and freshwater content, and its relation to the cryosphere, and sea level (ST2.3), as well as acidification, deoxygenation and their impact on the carbon cycle and marine ecology (with T6).

- **D2.4 (2027):** Quantification of natural versus anthropogenic influence on the AMOC and associated impacts on global and European climate. **M2.4-1 (2025):** Provision, analysis, modeling and synthesis of data acquired from long-term observatories in key regions (e.g., AtlantOS/EuroSea, INTAROS, Fram Strait, OSNAP, HAFOS) to quantify anthropogenically introduced changes. **M2.4-2 (2025):** Eddy-resolving climate model configurations available to assess natural and anthropogenically forced oceanic and atmospheric processes (link to ST1.2).

[54] 'Böning CW, et al. 2016. Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean. Nature Geoscience. 9:523-527.

Lessons from the past. The rapidity of the anthropogenically forced global climatic changes has no true analog even in Earth's distant history. Nonetheless, dedicated paleo-reconstructions and modeling investigations of the ocean and the cryosphere on their way into and during past warmer-than-present conditions will enable a better understanding of the natural forcings and processes driving the mean state of the system at temperatures similar to those expected for the near future. This includes the warmer-than-present last interglacial (Eemian, 125,000 years ago), mid-Pliocene (3-3.5 Million years ago) and mid-Miocene (14-16 Million years ago) periods, during which temperatures similar to the expected 1.5°C, 2°C and 4°C future warming scenarios prevailed,[55] at least on a local and regional scale.

Existing and new material obtained during upcoming IODP/ICDP expeditions and with the entire German research fleet will be used to reconstruct changes in large-scale overturning circulation and ventilation in key regions directly impacting fluxes and storage of carbon, heat, trace elements, nutrients and their utilization in the North Atlantic, North Pacific and the Southern Ocean. This will include research on differences in geodynamic and tectonic boundary conditions, such as bathymetry, topography and oceanic seaways. CO_2-forced climate sensitivity estimates have mostly been derived from data and climate models that represent fast feedbacks within a century, which are, however, difficult to reconcile with the magnitude of climate changes in the past. Therefore, we will synthesize paleoclimate data and models to examine the complex response of the Earth system to natural external forcings including changes in carbon sinks and sources (link to T1, T5 and T6).

Consequences of changes in overturning circulation for land-ocean linkages including permafrost areas (link to T4 and T5) and the major eastern boundary upwelling areas will be studied and integrated with well-dated terrestrial records of environmental changes (i.e., ICDP). Foci will be the examination of tipping points and thresholds, such as shifts in the dynamics of the ACC and the AMOC and their linkages to the monsoonal system[56] and the Cenozoic history of polar climates. These marine records will be complemented by a new European ice core from Antarctica (BE-OI) to be obtained by an international consortium in which AWI plays a key role. This will allow tests of the ability of models to reproduce large-scale ocean-atmosphere-cryosphere-climate changes and lead to improved projections of future global and regional changes, which also benefits fisheries and biodiversity studies (T6).

- **D2.5 (2024)**: Concept for the implementation of a CTA on 'Earth System thresholds affecting globally relevant CO_2 sinks and sources'. **M2.5-1 (2022)**: Scoping workshop for the CTA involving experts from T1, T2, T4, T5 and T6 as well as external partners.
- **D2.6 (2027)**: Comprehensive reconstruction, synchronization, and modeling of major ocean and cryosphere changes and their forcing in key regions during past warming climates and during transitions into these. **M2.6-1 (2023)**: Global integration of sea ice cover, sea surface temperature, ocean circulation and terrestrial climate data for the last interglacial, approximating 1.5°C warmer than pre-industrial conditions (Eemian). **M2.6-2 (2023)**: EAISE expeditions to the Indian sector of the Southern Ocean to reconstruct the instability of the East Antarctic Ice Sheet (EAIS) (link to ST2.3). **M2.6-3 (2025)**: Recovery of the world's oldest continuous ice core in Antarctica (BE-OI). **M2.6-4 (2027)**: Evaluation of the proxy-based reconstructions beyond the presently prevailing range of climates by isotope-enabled Earth system modeling on multi-millennial time scales.

Infrastructures and specific resources. In order to carry out the planned research a wide range of standard and specific infrastructure and instrumentation is required. Clean laboratories and a range of modern mass spectrometers are available. We will use the entire German research fleet, including our LKII vessels, the research aircraft, the Neumayer III and Kohnen Stations, the AWIPEV research base on Svalbard, the Ocean Science Center Mindelo (OSCM) on Cape Verde, and employ oceanographic, atmospheric, geological, geophysical and biogeochemical instrumentation. We operate ocean observatories such as FRAM and the 53°N and 11°S arrays and state-of-the-art deep-sea instrumentation in modular configurations as in MOSES, including

[55] Burke KD, et al. 2018. Pliocene and Eocene provide best analogs for near future climates. PNAS. 115:13288–13293.

[56] *Gebregiorgis D, et al. 2018. Southern Hemisphere forcing of South Asian monsoon precipitation over the past ~1 million years. Nature Comm. 9:4702.

autonomous platforms, moored ocean observatories, profiling floats, ice-tethered systems, gliders and glider swarms as well as geophysical instrumentation. Furthermore, uncoupled and coupled climate model systems with capabilities for regionally refined resolutions (nesting in FOCI and unstructured meshes in FESOM) will be central infrastructures that will benefit from CTA ESM and CARF JL-ExaESM. The required high-performance computing infrastructure is described in ST2.4.

Cooperation partners. Strategic partners for the Arctic and Antarctic research are the key partners of our flagship activities like MOSAiC and BE-OI. In addition, international consortia such as SCAR Aspect, CLiC and the International Arctic and Antarctic Buoy Programs (IABP/IPAB) will be key to ST2.1. For the investigation of the AMOC variability there are close collaborations with WHOI, Duke University, RSMAS Miami, NOC Southampton, BAS, Ifremer, and DFO Canada in the frame of OSNAP to coordinate the observational programs and to model the data. Calibration of ocean circulation and biogeochemical proxies will be carried out in the frame of the international GEOTRACES program as well as with national partners (e.g., University of Kiel, Jacobs University Bremen, MARUM Bremen, University of Oldenburg). Long sediment records will be recovered in the frame of national research cruises and as part of the international IODP program (many expeditions led by T2 scientists). Additional material from continental records will be available via the ICDP program.

Risks and Opportunities. In ST2.1 major contributions to the long-term observing systems will be made. However, this work relies heavily on field observations and satellites, for which there are numerous risks such as technical failures, weather and ice conditions that may compromise airborne and marine surveys. Furthermore, the approach of using drivers of past warm periods for assessing future changes may have caveats given that the reconstructed temperatures are affected by major differences in Pliocene and Miocene dynamic factors and paleogeography. Possible technical difficulties may either complicate the planned extraction of the new long ice and sediment cores or the recovered records may not provide all the information anticipated (e.g., BE-OI, IODP). However, combined with appropriate models and adjusted boundary conditions this approach will provide an improved mechanistic understanding of the Earth system.

Subtopic 2.2 Variability and extremes

Thomas Laepple, AWI; Peter Brandt, GEOMAR

Scope and challenges. The ocean and cryosphere play an important role in shaping weather and climate across a wide range of spatial and temporal scales. This includes natural climate variability driven by internal processes and external natural forcings such as solar variability and volcanoes, as well as extreme events. Natural climate variability, resulting from interactions between and within the ocean, the cryosphere and other components of the climate system, is a major source of uncertainty for regional climate projections and sets the range of possible future scenarios. In addition, the evolution of and adaptation to extreme events in a rapidly warming world is a major challenge for society. Finally, ecosystems might be even more vulnerable to changes in variability and extremes than to changes in mean climate. However, the understanding of variability and extremes in a warming world is limited due to the short instrumental records and challenges of current climate models in accurately reproducing them. Closing the knowledge gaps requires time series that are longer than the instrumental record, a better mechanistic understanding of internal climate variations, and unraveling the feedbacks, coupling and nonlinearities within the climate system. ST2.2 addresses these challenges by exploiting unique observational capacities, know-how and infrastructure to create and interpret paleoclimate records, expertise in climate dynamics and the available advanced Earth system modeling capabilities. In doing so, the full spectrum of extreme events from weather to climate extremes (with T1) and the complete range of drivers and consequences from physics to regional ecosystem impacts (with T6 and T5) will be covered.

Main objectives. ST2.2 will unravel the structure and dynamics of natural decadal-to-centennial climate variability and improve its simulation in climate models. It will determine possible links between relatively slow natural climate variability and rapid climate extremes, and characterize and quantify extreme events in a changing climate on regional scales (e.g., heatwaves in Europe, sea ice minima in the Arctic and super El Niños in the tropics). Special attention will be paid to teleconnections between the tropics, polar regions and mid-latitudes. Finally, ST2.2 will determine environmental predictability on daily to decadal time scales and contribute to advanced forecasting capabilities.

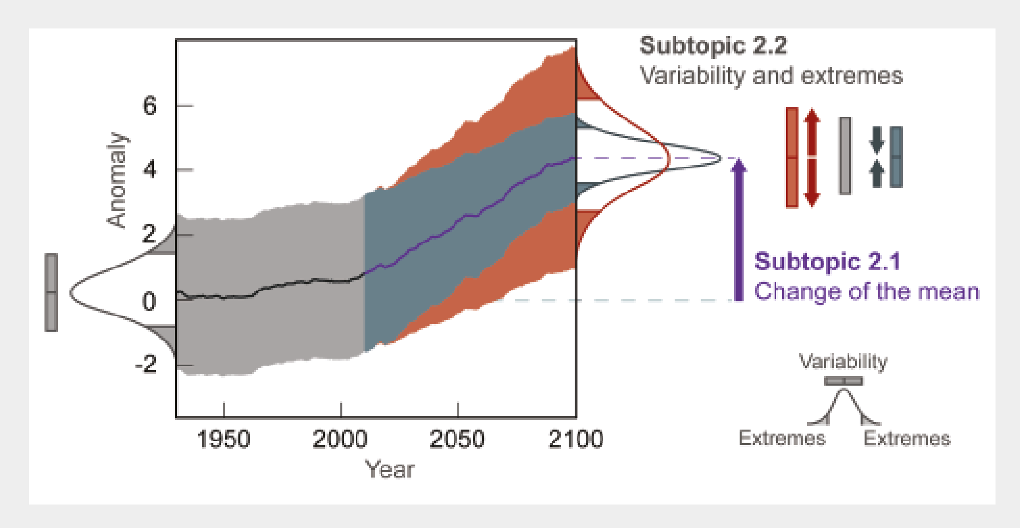


Fig. 2.4: Illustration of variability, extremes and mean state changes. For society and adaptation measures, the likelihood of specific events, such as the crossing of a temperature threshold, has to be known. This can be represented by a probability density function. Climate change can shift the entire distribution and its extremes (Focus of ST2.1) but can also broaden, narrow or distort the distribution, thus altering the variability and extremes (Focus of ST2.2). Shown is a climate time-series, its range of variability (2σ) and two hypothetical scenarios of increasing (red) or decreasing (blue) variability accompanying the increase of the mean.

Work program.

Quantifying and simulating natural climate variability. Climate variability on decadal to centennial time scales is currently not well constrained and existing climate models appear to be too stable in magnitude[57] as well as in the response of climate variability to mean climate changes.[58] The development of advanced proxy system models, novel statistical correction methods and optimized sampling and measurement techniques applied on newly taken sediment and ice core arrays will considerably reduce the existing uncertainty of variability estimates and result in a reconstruction of natural climate variability across spatial and temporal scales at unprecedented quality. Another limiting factor is the lack of knowledge of how natural forcings (e.g., solar variations) impact climate variability, in particular on regional scales. Furthermore, major uncertainties remain in the representation of natural climate variability and their governing processes in numerical models. Using the new variability reference dataset, to be developed in ST2.2, along with the improved dynamical understanding of natural climate variability, the performance of climate models in simulating the full spectrum of variability will be assessed. Given the possible link between climate variability and sensitivity, this also has the potential to better constrain transient climate sensitivity and feedback loops, thereby contributing to ST2.1. It is expected that model improvements (e.g., enhanced resolution and better representation of interactions between Earth system components) will reduce the uncertainties in amplitude and structure of simulated internal variability as well as the response to natural forcings. This will allow to better anticipate the full range of possible future climate change and the stability of the future climate system both essential to plan mitigation and adaptation measures. The ultimate goal is thus to enable better projections of the future global and regional climate evolution for 1.5°C, 2°C and 4°C future warming scenarios (including its full probability distribution, Fig. 2.4), which will result in major contributions to forthcoming IPCC reports.

- **D2.7 (2026):** Unprecedented observational reference dataset of spatio-temporal decadal to centennial temperature variability. **M2.7-1 (2023):** Optimized workflow established and tested for high-accuracy temperature variability reconstructions from paleo-records. **M2.7-2 (2024):** Completion of arrays of firn/ice cores in Antarctica and Greenland, and recovery of high-resolution sediment proxy data. **M2.7-3 (2026):** Completion of statistical variability reconstruction and merging with instrumental observations.

[57] *Laepple T, Huybers P. 2014. Ocean surface temperature variability: Large model-data differences at decadal and longer periods. PNAS. 114:16682-16687.

[58] *Rehfeld K, et al. 2018. Global patterns of declining temperature variability from the Last Glacial Maximum to the Holocene. Nature. 554:356-359.

- **D2.8 (2027):** Model configurations with fundamentally improved ability to simulate decadal to centennial-scale natural climate variability. **M2.8-1 (2025):** Impact of aspects such as enhanced ocean and atmosphere resolution in climate models on simulated natural climate variability established (link to ST1.2).

Variability and extremes: Links across time scales and compartments. Decadal-to-multidecadal variability is coupled both to phenomena on (synoptic) weather time scales such as atmospheric blocking situations, as well as to the long-term background conditions. As an example, meandering of the jet stream in the Euro-Atlantic region and associated blocking activity is linked to changes in the AMO and AMOC, implying the need for a proper representation of the ocean-sea ice system as well as synoptic scale variability in coupled climate models. We will use a hierarchy of global climate simulations and a wide range of observational, (paleo-)environmental and reanalysis data to evaluate variability patterns and extreme events on synoptic to millennial time scales. This is also facilitated by including isotopes in climate models allowing to directly simulate paleo proxy data.[59] This integrated approach provides a long-term context on the links between time scales and compartments beyond our limited view based on the observational period.

- **D2.9 (2027):** Extensive evaluation of climate patterns and extremes across synoptic to millennial time scales. **M2.9-1 (2022):** High-resolution model configuration based on OpenIFS and FESOM2 established. **M2.9-2 (2023):** Isotope modeling and data assimilation capacity established in Earth system models. **M2.9-3 (2025):** Assessment of the link of North Atlantic blocking, jet stream and variability across time scales and climate backgrounds (ST1.3, HI-CAM).

Changes in the intensity and frequency of extremes. Extreme events such as sea ice minima in the Arctic have drawn widespread attention during recent decades due to their large socio-economic impacts (e.g., on shipping). ST2.2 will use unique long-term observations and model experiments to study marine and polar extreme events like ocean and atmosphere heatwaves, sea ice minima, warm air intrusions in the Arctic and mesoscale Arctic cyclones. By examining the potential of using paleoclimate proxy data to explore changes in the frequency of occurrence of past weather extremes in Europe (e.g., strong rainfall, floods, droughts) along with associated atmospheric circulation regimes at seasonal resolution, the analysis of the instrumental period in T1 will be complemented. This will result in time series of extreme events ('paleo weather') that will be important for quantifying future risks.

The role of climate change in triggering prominent extreme events, such as the European heatwaves in summer 2018 and 2019 that have been linked to a strongly meandering jet stream, is still unclear and will be investigated (link to CARF HI-CAM and T1). This includes investigations of how the jet stream and thus the intensity and frequency of extreme events will change in the future. Furthermore, we will explore novel 'storyline scenarios'[60] using spectral nudging approaches that will provide insight into the question of how prominent extreme events would have unfolded in 1850 (pre-industrial) and might unfold in the future for different temperature evolution pathways. Focusing on scenarios for recent extreme events that are fresh to people's memory, will facilitate a better communication of climate change to society and thus improve adaptation.

- **D2.10 (2026):** Quantification of changes in the intensity and frequency of weather and climate extremes. **M2.10-1 (2023):** Attribution of jet stream drivers of recent European extreme events (link to ST1.3 and HI-CAM). **M2.10-2 (2024):** Extreme event-time series spanning several millennia based on seasonally resolved records from lake sediments, ice cores and bivalves combined with forward models and data assimilation. **M2.10-3 (2026):** Interpretation of paleoclimate data and related weather and climate patterns ('paleo weather').

Tropical upwelling systems. Another focus will be the study of tropical upwelling systems that are among the most productive ecosystems in the world, control the oxygen distribution in the subsurface ocean and are fundamentally important for fisheries and food security (link to T6). Warming, variability and extremes in upwelling systems are associated with major climate modes and their teleconnections such as the Pacific El

[59] *Werner M, et al. 2018. Reconciling glacial-interglacial changes of Antarctic water stable isotopes, ice sheet topography, and the isotopic paleothermometer. Nature Comm. 9:3537.

[60] *Shepherd TG, et al. 2018. Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. Clim Change. 151:555-571.

Niño, Benguela Niño, or the Atlantic Meridional Mode. On millennial time scales, rapid shifts in the nutrient supply to the tropical Atlantic were associated with changes in Southern Ocean upwelling and ocean circulation at intermediate depths,[61] which will be investigated in all three major ocean basins for extended periods in the past. A coordinated campaign will be designed to decipher the physical drivers of ecosystem variability in the NW African upwelling system based on state-of-the-art shipboard and autonomous observations, and improved nested ocean and climate models.

- **D2.11 (2026):** Improved understanding and representation of ocean-system dynamics and processes in tropical upwelling regions in ocean and climate models and for the benefit of operational upwelling forecasts (e.g., CMEMS). **M2.11-1 (2023):** Campaign design for dedicated upwelling study with focus on the West African upwelling system, including impacts on marine ecosystem and fisheries, in cooperation with local African and international partners (link to T6). **M2.11-2 (2025):** Attribution of tropical upwelling variability and extremes to local and remote processes associated with different climate modes.

Linkages between tropics, polar regions and mid-latitudes. A key challenge to improve our understanding and prognostic capabilities of extreme events in the atmosphere, ocean and sea ice, is the attribution to distinct local and remote drivers. One important area of research involves 'modes' of internal climate variability, which effectively link low and high latitudes. A prominent example is the El Niño/Southern Oscillation (ENSO) phenomenon. Using observations and improved numerical models, we will investigate how these teleconnections behave under climate change[62] (e.g., super El Niños) and thus affect extreme events in the mid-latitudes.

Another prominent example is the possible impact of rapid Arctic sea ice decline on extreme weather patterns in mid-latitudes. We will address the question of why state-of-the-art models show a rather weak and variable response to Arctic sea ice decline, and whether advanced models provide different responses. Model experiments will be carried out exploiting protocols such as the Polar Amplification Model Intercomparison Project (PAMIP).

- **D2.12 (2025):** Quantification of the linkages between the Arctic and lower latitudes, taking into account atmospheric and oceanic processes. **M2.12-1 (2023):** Experiments with advanced models (revised parametrizations, increased resolution and interactive ocean) following the PAMIP protocol.

Predictability on daily-to-decadal time scales. ST2.2 will improve the understanding of the inherent limits of predictability of the climate system, from daily-to-decadal time scales. On shorter daily-to-subseasonal time scales, the focus will be on establishing the limits of predictability of Arctic sea ice, including small-scale features such as sea ice leads, which are relevant for shipping. On subseasonal-to-seasonal time scales, aspects such as stratosphere-troposphere interaction play a role, and for seasonal-to-decadal time scales the role of the ocean and the decadal-scale solar cycle move into the focus.

Work on fundamental predictability limits will be augmented by research that advances actual prediction systems in collaboration with strategic partners. For example, we will explore improvements of various polar and global observing systems to advance forecast skill (including extreme events). Furthermore, recommendations will be made regarding the modeling of critical aspects of the ocean and cryosphere. Forecasting will also benefit from research on coupled data assimilation (link to ST2.4). Knowledge will be transferred into operational prediction systems, through collaborations at the European and international level, and projects that bring together academic research institutes and operational forecast centers, such as WMO's Year of Polar Prediction (YOPP)[63] or the WCRP Near-Term Climate Prediction Grand Challenge, or activities related to the prediction of future upwelling conditions in the tropical Atlantic.

- **D2.13 (2025):** Quantification of the skill of operational prediction systems (e.g., ECMWF) in strategically relevant regions. **M2.13-1 (2022):** Initial assessment of the relative importance of various components of the observing system for skillful (polar) predictions. **M2.13-2 (2023):** Assessment of existing operational systems for the prediction of sea ice characteristics on time scales from days to seasons.

[61] *Poggemann D-W, et al. 2017. Rapid deglacial injection of nutrients into the Atlantic via Antarctic Intermediate Water. Earth and Planetary Science Letters. 463:118–126.

[62] *Latif M, et al. 2015. Super El Niños in Response to Global Warming in a Climate Model. Clim Change. 4:489–500.

[63] *Jung T, et al. 2016. Advancing polar prediction capabilities on daily to seasonal time scales. Bull. Amer. Meteor. Soc. 97:1631–1647.

Infrastructures and specific resources. The requirements are comparable to those of ST2.1. The required supercomputing infrastructure is described in ST2.4.

Cooperation partners. Strategic partner for the Greenland-based research is PICE-Physics of Ice, Climate and Earth, University of Copenhagen. Tropical observations contribute to the Tropical Atlantic Observing System in cooperation with the international PIRATA program. In addition, model intercomparison projects of the WCRP in support of IPCC assessment reports such as CMIP, PMIP, PAMIP and HighResMIP, and the WCRP Grand Challenge Near-Term Climate Prediction will play an important role, as will WMO's Year of Polar Prediction, which also provides critical links to operational prediction centers. ST2.2 will also build on extensive networks established through European consortia such as APPLICATE and PRIMAVERA. Work in ST2.2 will complement research in T1 by providing the long-term context through paleo-observations, focusing on the oceanic and cryospheric perspective on extremes. The work will be linked to the CARF REKLIM theme 'Extreme events across temporal and spatial scales'.

Risks and Opportunities. Deciphering the processes that govern natural climate variability and extreme events and their changes under global warming, may reveal gaps in process identification and system understanding. A particular risk is the potentially low signal content in paleo proxy data. We will address this by advanced proxy development (ST2.4), proxy system modeling combining independent proxy data and replication strategies. While improvements in predictive capacity (for example, of tropical upwelling systems) is of high societal relevance, identified forcing factors and relevant physical processes may be dominated by stochastic variations rather than by predictable signals (resulting in only weak improvements in forecast systems). Generally, high-resolution model configurations are expected to better simulate variability and extreme events. However, technical challenges related to scalability bottlenecks need to be tackled to exploit their full potential on exascale high-performance computers (see ST2.4).

Subtopic 2.3 Sea level change

Maik Thomas, GFZ; Torsten Kanzow, AWI

Scope and challenges. Global sea level has been rising at a rate of 3 mm per year throughout the last decades, largely as a consequence of ocean warming and ice sheet mass loss. It is projected to rise at an even higher rate in the future. From paleoclimate data, we know that sea level rise could exceed 40 mm per year (e.g., during the transition from the last glacial maximum to the Holocene). Some of the contributions to modern sea level change are well understood, such as thermal expansion. However, there have also been surprises such as the ice sheets of Greenland and Antarctica having turned into major contributors to present-day sea level rise within just two decades. Carrying out trustworthy projections how sea level will rise in the future is of utmost importance. In this context, providing information for regional and local coastal regions will be crucial, as rates may differ substantially from the global trend due to regional patterns of warming (or cooling), wind- and buoyancy-driven ocean circulation and ice-ocean-solid Earth interactions manifesting as self-gravitation, isostatic adjustment or subsidence.

The scope of ST2.3 is to provide the scientific underpinning for advanced assessments of both global and regional sea level change, including their attribution to individual causes, past and recent trends and future projections. In the open ocean, changes in sea surface heights can be precisely and continuously observed with satellites at almost global coverage. However, some of the individual causes of observed sea level changes are still poorly understood. Our vision is to quantify and project sea level change from polar sources to the coasts (with T4). We will assess to what extent critical processes, such as those triggering and forcing ice sheet mass loss, surface deformation, self-gravitation or ocean circulation changes, contribute to present-day sea level change, which will enable more trustworthy projections of future sea level rise. To make our assessments applicable for decision-makers, a particular emphasis will be on providing the best possible range of uncertainties of the different contributions to sea level change over well-defined time horizons and on implementing effective knowledge transfer.

Main objectives. We aim to develop and implement sustained monitoring and reconstruction capacities of both sources and regional distributions of sea level change. The combination of present-day observations and process modeling with reconstructions based on proxy-based records of past sea level changes associated with ice sheet collapses will allow us to gain critical understanding of processes that are currently not well represented in Earth system models. Furthermore, we intend to quantify global and regional sea level changes. By combining complementary monitoring systems as well as forward and data-constrained modeling approaches, we will separate and quantify individual processes, in particular, changes in ocean mass and heat content, continental discharge and ice mass balances, and deformation-induced changes in basin geometry. These activities will guide the development of an advanced Earth system model that is capable of simulating sea level changes with unprecedented trustworthiness. We also aim to provide regional projections of sea level change with well-defined uncertainties arising from both, climate scenarios and sources of sea level change. Through collaboration with coastal modelers in T4, information about coastal sea level change will be provided.

Work program.

Antarctic and Greenland ice sheet mass loss. In order to assess the impact of the future evolution of the Antarctic and Greenland Ice Sheet mass loss on sea level, we will establish monitoring and reconstruction capacities to track non-linear pathways towards fast ice discharge (tipping points) related to marine ice sheet instabilities. We will investigate three key ocean-ice sheet systems that currently reside in different states. Firstly, the Amundsen Sea Embayment of the West Antarctic Ice Sheet (WAIS)-ocean system has most likely already entered a mode of fast discharge. Through our involvement in both IODP and the International Thwaites Glacier Collaboration (ITGC) we will establish reconstruction capability of past ice sheet changes, while remote sensing will track its current state with crucial contributions expected from GRACE-FO. Secondly, the North-East Greenland Ice Stream (NEGIS) system shows signs of significant ocean-driven thinning of its major outlet, the 79° North Glacier (79NG). Ocean and ice-based studies as well as air- and space-borne remote sensing will establish the trajectory of the NEGIS system. Thirdly, the Filchner-Ronne ice shelf (FRIS) in the Weddell Sea is not yet showing major signs of change, but the frontal continental shelf is prone to intrusions of warm open-ocean water. We will address past tipping points and potential for ice mass loss of other relevant sectors of the EAIS (Enderby and Wilkes Land sectors).

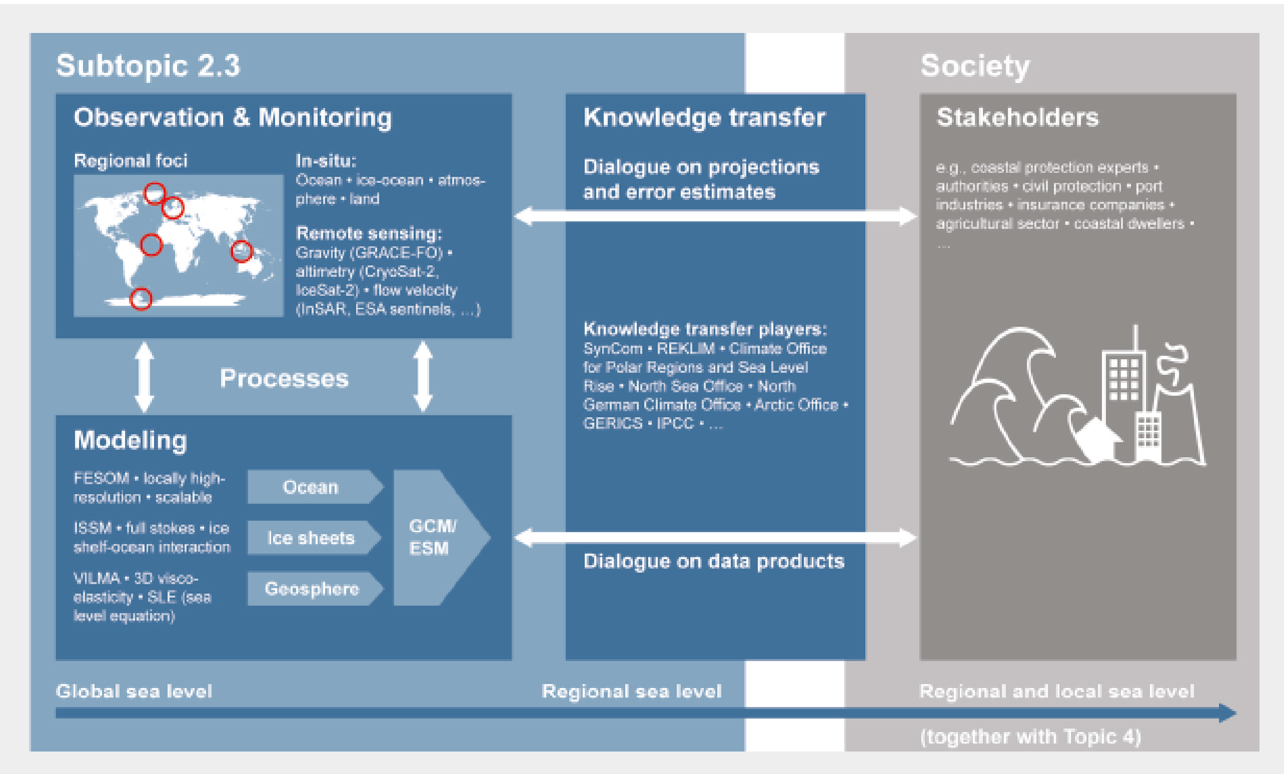


Fig. 2.5: Overall structure and aims of ST2.3 with an illustration of the value chain approach employed in Topic 2.

Simulations suggest that the FRIS could reach a tipping point as a consequence of increasing ocean heat transport before 2100.[64] Repeated sea-going expeditions in the Weddell Sea will provide crucial data for refining our understanding of ocean-driven processes and their interactions with ice. Combined analyses of bathymetric, geophysical and geological information along the Antarctic Shelf will enable an integrated 3-dimensional investigation of the past ice sheet extent, flow patterns of paleo-ice streams, and grounding line retreats. These efforts, combined with present-day internal ice sheet structure analyses, provide a long-term perspective of changing ice dynamics related to ice shelf collapses, which is crucial for understanding the sensitivity of ice stream discharge.

To thoroughly quantify the current development of sea level patterns, we will improve radar altimetry observations[65] spanning the past three decades and reduce the error budget of the measurements by combining geodetic observation methodologies (altimetry, tide gauges, GNSS, satellite gravimetry, precise and stable geodetic reference frame). The integration of different sensors and methodologies will enable an accurate assessment of global, regional and near-coastal sea level changes. Our assessments will be global, taking into account hotspot regions like the Polar Seas, and the shelf seas of Western Europe and of Southeast Asia. In addition, the GRACE-FO mission will facilitate improved estimates of ocean and ice sheet mass changes, a prerequisite for a better distinction of barystatic and steric sea level changes.

- **D2.14 (2024):** Established present state and improved paleo-dynamic history of key ice sheet systems (WAIS, NEGIS, 79NG). **M2.14-1 (2022):** COSMUS and ATWAICE expeditions to install infrastructure for year-round observations of warm water flow toward the FRIS and 79NG cavities complemented by on-ice and airborne observations. **M2.14-2 (2023):** IODP and ITGC data analysis completion. **M2.14-3 (2024):** Combined analysis of GRACE-FO and altimetry with respect to ice mass balances.
- **D2.15 (2026):** Established capabilities for global to regional sea level monitoring. **M2.15-1 (2024):** Established ground-truthing infrastructure to monitor stability and error budget of altimetry (tide gauges, GNSS profiling). **M2.15-2 (2026):** Operating workflows for timely combination of monitoring systems (altimetry, tide gauges, GNSS, satellite gravimetry, magnetic field observations) describing state and development of sea level. **M2.15-3 (2026):** Established consistent deformation model for loading correction in monitoring systems.

Attribution of causes of regional and global sea level change. Major processes regarding causes of regional and global sea level change, such as load-induced surface deformation, subsidence or self-gravitation, are often not considered in state-of-the-art Earth system models. We will work toward an attribution system for sea level change taking several steps. By combining satellite- and in situ monitoring data with forward and constrained modeling approaches we will separate and quantify individual processes contributing to sea level change, such as ice sheet mass loss, thermo- and halosteric expansions, loading, self-gravitation or continental freshwater fluxes. Important processes considered will be ocean-induced glacier and ice sheet retreat including basal melting and grounding line migration in ice shelf cavities. The analysis of residuals from model simulations simultaneously constrained by complementary observations will allow consistency checks of monitoring systems and, thus, provide reliable estimates of uncertainties.

For the establishment of a reliable attribution system a coupled Earth system model will be significantly extended in order to comprehensively account for ice sheet dynamics and ice-ocean-geosphere interactions, including ocean circulation in ice shelf cavities, grounding line migration, surface-loading and self-gravitation. Based on the capacities developed earlier and informed by proven forward and constrained modeling approaches, we will validate the capability of models to simulate collapses of the Antarctic Ice Sheet and reproduce regional patterns of past up to present-day sea level change.

- **D2.16 (2024):** Establish a system of spatio-temporal boundary conditions based on satellite, in situ monitoring and paleo proxy data for data-constrained modeling approaches. **M2.16-1 (2023):** Determination of sensitivities of present-day ocean-driven melt to changing environmental conditions in key ocean-ice

[64] *Hellmer H, et al. 2012. Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current. Nature. 485(7397):225–228.

[65] *Esselborn S, et al. 2018. Orbit-related sea level errors for TOPEX altimetry at seasonal to decadal timescales. Ocean Science. 14:205-223.

sheet systems (FRIS, 79NG, Thwaites). **M2.16-2 (2023):** Provision of uncertainty estimates from model runs simultaneously constrained by complementary observations.

- **D2.17 (2025):** Establish attribution systems of recent regional and global sea level change. **M2.17-1 (2023):** Incorporation of critical physical processes in the Earth system model (e.g., interactive ice sheets, interactions with the geosphere, loading, self-gravitation). **M2.17-2 (2024):** Reconstruction, monitoring and modeling capacity of trajectories of key ocean-ice sheet systems toward tipping points of marine ice sheet instability. **M2.17-3 (2025):** Generate time-dependent fingerprints to recent ice mass loss.

Sea level projections. Finally, we will provide regional sea level projections along well-defined time horizons, including improved estimates of uncertainties, based on advanced Earth system models that i) allow for dynamical coupling between oceans, ice sheets (including full Stokes physics), atmosphere and geosphere, ii) have regionally enhanced resolution through unstructured mesh methodologies, and iii) are highly scalable. By employing existing models, which typically have coarse-resolution and neither include interactive ice sheets nor consider effects arising from self-gravitation, surface loading or interactions with the geosphere, we will deliver an initial set of projections, which serve as a baseline against which the advanced Earth system models will be tested. Furthermore, sensitivity experiments will be carried out to establish the relative importance of underlying processes. These analyses will put earlier projections and associated uncertainty estimates of sea level change into perspective.

- **D2.18 (2025):** Regional sea level change projections for the years 2030, 2050, 2100 for pathways into 1.5°C, 2°C and 4°C warmer worlds. **M2.18-1 (2023):** Establish initialization capacity that allows sea level change scenarios to capture aspects of observed/reconstructed trajectories. **M2.18-2 (2024):** Provide first set of sea level change projections as a basis for coastal projections planned in T4 and to compare against CMIP6 projections.

Infrastructures and specific resources. ST2.3 relies on infrastructure which allows in situ observations and remote data retrievals. This includes: i) ships such as RV Polarstern for oceanographic, geoscientific and glaciological continental and ice shelf surveys, ii) satellite gravity and altimetry missions such as GRACE-FO and SAR altimeters (CryoSat-2, SENTINEL-3), iii) permanent and summer stations with related overland traverse capabilities for on-ice missions such as Neumayer-Station III, iv) surface-based operations by airborne missions, specifically polar airplanes, and v) tide gauge and GNSS networks, and the Lake Issyk Kul (Kyrgyzstan) ground-truthing facility for satellite altimetry. The demanding modeling activities require sufficient computing resources, large-storage space and fast interconnection of computing and storage facilities at the different centers (cf. ST2.4).

Cooperation partners. Our cooperation ranges from complementing groups at universities to European and international institutions. Partners include Jet Propulsion Laboratory (USA) for ice-dynamic modeling and GRACE-FO, PICE (DK) for operations in Greenland, the ITGC (US NSF, UK NERC-BAS) and links established in the framework of the Filchner Ice Shelf System and Filchner Ice Shelf Project (NERC-BAS, Norwegian Polar Institute, University of Bergen) for joint logistical and scientific operations in Antarctica. A newly established cooperation in the framework of the Arctic Science Partnership with ocean scientists from Greenland (GINR) will provide fieldwork access to the ocean-glacier systems around Greenland and extensive scientific knowledge of these systems.

Our research will rely on our strategic links to UNESCO/GLOSS for the assessment of tide gauges, GGOS for maintaining the precise global reference frame, and NASA for the operation and analysis of the GRACE-FO mission. We will engage in selected partnerships in order to fill critical gaps in sea level research not covered by ST2.3. Specifically, a bilateral partnership to the Universities of Utrecht (NL) and Liège (BE) is being established for surface mass balance modeling of ice sheets. Additionally, we will strengthen the existing link to the World Glacier Monitoring Service (WGMS) and to the Priority Research Program SPP1889 'Regional Sea Level Change and Society' of the DFG, funded until 2022. This will also bridge the gap to experts of socio-economic entities, which are our stakeholders.

Risks and Opportunities. The observational part naturally runs the risk of not obtaining data, for example because of cancellation of expeditions, insufficient availability of ship time, problems in the realization of satellite missions, failure of instruments or other logistical challenges. However, the work program is sufficiently diverse and thus resilient to provide the majority of deliverables. After three decades of operational radar altimetry this work program puts us in the position to use the upcoming and entirely new technology to close observation gaps in near-coastal regions. Likewise, more precise time-variable gravity fields will lead to improved estimates of different sources contributing to sea level change. New modeling activities, such as CTA ESM and the ongoing development of a national strategy for Earth system modeling in Germany, provide new opportunities for exploiting synergies by bringing together complementary expertise.

Subtopic 2.4 Advanced research methodologies for tomorrow

Gesine Mollenhauer, AWI; Frank Flechtner, GFZ

Scope and challenges. Research in STs 2.1 to 2.3 requires methodologies that reach beyond what is currently available. In situ observations of ice and the polar, open and deep ocean are challenging due to harsh environmental conditions, and need specifically adapted, inter-calibrated sensors on year-round deployable platforms, tethered and autonomous robots capable of navigation in under-ice, deep-sea or extreme weather conditions, and improved remote sensing technologies. Unraveling past Earth system states requires new proxies from ice and sediment cores and the corresponding development of new analytical techniques. The fidelity of paleo proxies, in particular in quantitative terms, demands careful assessments of biases, calibrations and parallel development of complementary approaches. Precise chronological control and coupling of sediment and ice core archives remains a challenge. Simulating critical processes more realistically requires new parametrizations, major increases in resolution and incorporation of new model components. Observations and model output, both in volume and variety of variables, call for enhanced assimilation and data science capabilities to unlock hidden information. The development of advanced observational, modeling and analytical capabilities and proxy methodologies will be realized in concert with the scientific needs formulated in the other Subtopics and in collaboration with T1, T4, T5, T6, and T7. Work will benefit from existing experience in coordinating the implementation of new methods in EU projects (e.g., AtlantOS/EuroSea) and within Helmholtz (e.g., CTAs ESM and MOSES).

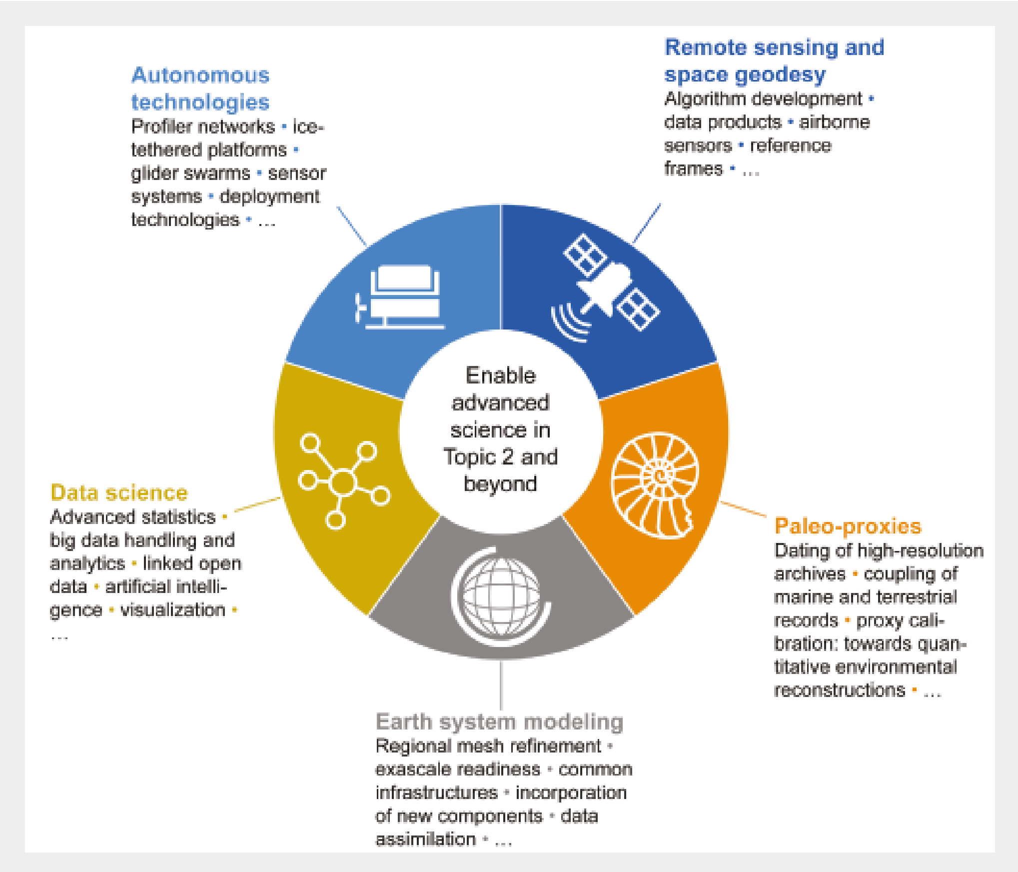


Fig. 2.6: Major research methodologies addressed in ST2.4.

Main objectives. The main objective of this Subtopic is to improve the methodological basis of research carried out in T2 and beyond. This will be achieved through the development of new observational techniques (e.g., modular observing systems, such as MOSES, FRAM, ARCHES and SMART cables; upgrade of robotic technologies by joint investments as proposed in MUSE), space geodetic observations (e.g., proposed next-generation MCM, innovative GNSS applications, contributions to the SLR and VLBI Global Observing Systems), paleo proxies (e.g., advanced proxy calibrations, chronologies, synchronization of archives) and novel modeling capacities (e.g., global modeling with regionally refined resolution and data assimilation techniques), including models that capture a wide range of resolutions and processes (e.g., tides, surface waves). The rapidly evolving field of data science will also be exploited (e.g., efficient analysis of big data, machine learning, visual analytics).

Work program. ST2.4 is composed of five main research areas: Autonomous Technologies, Remote Sensing and Space Geodesy, Proxy Analysis, Earth System Model Development and Data Science.

Autonomous Technologies. We deploy and continuously advance mobile autonomous oceanographic and biogeochemical observatories for continuous, long-term, and large-scale data recording as well as for direct interaction with the environment (e.g., the Argo hydrographic profiler network or ice-tethered platforms). To assess specific processes (e.g., at the continental slope and shelf) autonomous gliders and glider swarms will deliver multi-parameter datasets. Coordinated applications of autonomous observing technology will be implemented via modular observing concepts from infrastructures such as MOSES or ACROSS.

Autonomous systems are also of major importance for research in remote polar and deep-sea environments, and they enhance the meso- to sub-mesoscale observational capabilities of shipboard campaigns. Challenges from power supply to resilience in harsh polar environments, ice-covered oceans and the deep sea, require technical solutions. These include the development of appropriate sensor systems (e.g., fiber optics, SMART cables, mobile platforms and stationary moorings in ice-covered areas), state-of-the-art deployment technologies (e.g., hot water drilling for accessing the ocean beneath ice shelves), as well as clean sampling strategies (from air, snow, sea water and sediment), remote communications to transmit autonomously acquired data, the development of robots that allow monitoring and object manipulation in the deep sea (ARCHES), and their long-term energy supply via submarine fuel cells (ARIM-FUEL).

Remote Sensing and Space Geodesy. Algorithm development for novel data products of wider and societal relevance for various satellite sensors in support of glaciology, geophysics and sea ice research is a priority. Here we aim at multi-mission products and their combination with airborne and ground-based data, including applications to upcoming missions (e.g., next-generation MCM[66]). Advanced SAR processing for satellite-borne (e.g., PolinSAR, SAR/InSAR) and airborne systems will elucidate ice sheet and sea ice structure and improve near-coastal sea level estimation. Studies of long-term sea level changes require improvements in the stability and consistency of the International Terrestrial Reference Frame (ITRF). With a denser coverage of space geodetic core sites, an ever-increasing number of observing stations, and new analytical methodologies, such as co-location in space, new levels of accuracy can be expected. Using new airborne sensors, small-scale near-surface processes like turbulence over ice-covered polar oceans or the amount and propagation of ship emissions in the Arctic will be investigated. For the assessment of melt processes on ice surfaces, hyperspectral technology and topo-bathymetric laser scanning will be further developed.

- **D2.19 (2025)**: Contribution to a highly precise ITRF that improves the current state towards GGOS requirements. **M2.19-1 (2021)**: Simulation studies which include space-ties (i.e., co-location on satellites). **M2.19-2 (2023)**: Completion of advanced methodologies and algorithms for space geodetic technique analysis and combination of GNSS, SLR, VLBI, and DORIS.

Proxy Analysis. Investigating past climate variability, extreme events and processes in past periods of warmer climates requires dating of paleo-archives at the highest possible temporal resolution and a precise coupling between different archives (ice cores, marine sediments, lake sediments). To achieve this, we will advance the use of cosmogenic nuclides (^{10}Be, ^{26}Al) and the full range of uranium-series radionuclides as well as tephrochronology as chronological markers. These approaches will allow dating certain archives at annual

[66] *Dobslaw H, et al. 2016. Modeling of present-day atmosphere and ocean non-tidal de-aliasing errors for future gravity mission simulations. Journal of Geodesy. 90(5):423–436.

precision or will provide absolute dating of records of the more distant geological past (e.g., back to 1.5 Ma as in Beyond EPICA).

Development and calibration of isotopic, elemental and organic proxies will provide improved tools for the reconstruction of climatically driven changes in past environmental conditions. This includes carbonate system proxies and corresponding ages ($\Delta^{14}C$) allowing a quantitative reconstruction of glacial carbon storage and its release during warming phases of Earth's history (in close collaboration with T6). Another focus will be the development of element/Ca ratios in marine carbonates to quantify past ocean salinity and thereby precipitation and freshwater inputs. Past nutrient cycling will be reconstructed using stable Si isotopes in diatoms and deep-sea sponges (link to T6), while stable oxygen isotope analyses of biogenic opal will serve as a salinity proxy for high latitude regions. The use of radiogenic isotopes and Rare Earth Elements as proxies for weathering inputs and ocean circulation will be advanced through improved understanding of their biogeochemical cycling and their distributions along global sections in today's ocean (as part of the international GEOTRACES program). Moreover, water isotopes in ice core samples will be integrated with impurity measurements and constraints from diffusion length estimates and bore-hole temperatures to overcome the current limitations of ice core-based climate reconstructions. The accuracy and time-resolution of sedimentary and ice-based proxy archives will be improved through signal modeling and statistical deconvolution techniques.

- **D2.20 (2027):** Improved understanding and application of proxies for the quantitative reconstruction of key marine and cryospheric parameters. **M2.20-1 (2024):** Provision of a consistent age control for a marine reference sediment core including the use of radionuclide and cosmogenic nuclide techniques **M2.20-2 (2026):** Comprehensive parallel reference record of multiple proxies for this core (including $\delta^{11}B$, $\delta^{7}Li$, Na/Ca, $\Delta^{14}C$, HBI biomarkers) to advance internal and external agreement between proxies and archives.

Earth System Modeling. Global coupled ocean-atmosphere-sea ice models will be developed that are exascale-ready and capable of simulating decadal to centennial changes at mesoscale and sub-mesoscale resolutions for the sea ice-ocean components. Through the CTA ESM, we contribute concepts for regional refinements through unstructured meshes (FESOM) and nesting (FOCI/NEMO-AGRIF), respectively,[67] which will be shared with other partners (e.g., T1 and T6).[68] The ambitious high-resolution frontier simulations require significant investments to make the models and associated workflows exascale-ready (link to CARF JL-ExaESM). This includes new program structures using the concept of 'separation of concerns',[69] including domain-specific languages, new numerical techniques, and adaptive grids (e.g., for ice sheets). Improved simulation of natural climate variability, advanced ice sheet models (e.g., Ice Sheet System Model) and Solid Earth models (e.g., the Viscoelastic Lithosphere and Mantle model VILMA) will also be incorporated in Earth system models. Data assimilation and inversion techniques permit optimal monitoring design, such as mooring networks or autonomous system deployments, help to initialize model predictions, assess the origin of model errors, and develop improved model parametrizations. Existing data assimilation capacity centered around the Parallel Data Assimilation Framework (PDAF[70]) will be further developed, including nonlinear methods for high-resolution model configurations on HPC systems.

- **D2.21 (2023):** High-resolution global climate model components able to explicitly resolve meso-scale features such as ocean eddies and sea ice leads in dynamically relevant regions. **M2.21-1 (2021):** Coupled climate models with regionally refined resolution through nesting and unstructured mesh approaches. **M2.21-2 (2022):** Sea ice-ocean model components that are highly scalable on exascale computers.

Data Science. Similar to other fields, the marine and cryospheric sciences are increasingly facing large and complex informatics challenges. We will develop core expertise in data science – spanning advanced statistics, big data handling and analytics, Linked Open Data, Artificial Intelligence (AI, comprising machine learning

[67] *Biastoch A, et al. 2018. Simulating the Agulhas system in global ocean models – nesting vs. multi-resolution unstructured meshes. Ocean Modell. 121:117–131.

[68] At the same time, T2 will benefit from developments in other Topics (e.g., ICON in T1 and biogeochemical models in T6).

[69] Lawrence BN, et al. 2018. Crossing the chasm: how to develop weather and climate models for next generation computers. Geosci Model Dev. 11:1799–1821.

[70] *Nerger L, Hiller W. 2013. Software for Ensemble-based Data Assimilation Systems – Implementation Strategies and Scalability. Computers and Geosciences. 55:110–118.

and knowledge representation), and data visualization. A series of pilot programs has been started through projects in the Helmholtz Information & Data Science Incubator (see below). The 'Helmholtz School for Marine Data Science' (MarDATA) will play a leading role in the development of data science capacity and in the education of the next generation of marine data scientists. Among other applications, AI holds promise in improving signal identification, parameterizations in climate models and in the analysis of large observational datasets. Further, the computational efficiency and cost-effectiveness of cloud processing will be assessed by establishing processing chains for large data volumes. The efficient flow and interoperability of datasets from different origins is a bottleneck to end users. Therefore, we will extend the concepts developed for FRAM and Observations to Archive, including advanced automatic quality controls of data from multiple sensors and the generation of advanced data products available to the wider scientific community. This will be linked to new joint data initiatives of the RF E&E (see Ch. 1.4.2), including enriched metadata according to the FAIR principles (Helmholtz Incubator), and improved, networked data infrastructures (RF E&E data hubs, see below F).

- **D2.22 (2025):** A range of data science methods will be applied to analyze observational and model data. **M2.22-1 (2022):** Establishment of a core group including data scientists to provide advanced methodologies. **M2.22-2 (2023):** A first cohort of marine data scientists will finish their education through MarDATA.

Infrastructures and specific resources. Robotic systems and sensor platforms are constantly improved by all partners, and include a range of marine, land and airborne technologies, as well as new robotics. The Modular Earth Science Infrastructure (MESI) provides access to satellite systems (GRACE-FO), ground segments (Satellite Receiving Station Ny Ålesund), geodetic observatories (SLR Station Potsdam, GNSS), satellite data systems (ISDC, GravIS), and contributes significantly to several IAG services. Analytical facilities, in particular instrumentation optimized for analyses of small samples or trace amounts, include the miniature radiocarbon dating system (MICADAS) and a range of mass spectrometers and clean laboratories. For numerical modeling, all partners maintain a range of in-house facilities (Tier 3 systems) for smaller simulations and flexible access. Larger facilities are available through the Tier 2 system of the German Climate Computing Centre (DKRZ) and the 'Norddeutsche Verbund zur Förderung des Hoch- und Höchstleistungsrechnens' (HLRN) as well as the Tier 0/1 system of the Jülich Supercomputing Centre (JSC). CTA ESM continues to play a central role in providing infrastructure and guiding the discussion towards a national Earth system modeling strategy.

Cooperation partners. GEOMAR and AWI are well connected to the national and international marine infrastructure community through DAM and European alliances for seagoing technologies and the international GEOTRACES community, which consists of members from all leading international and national institutions working on trace elements and their isotopes. GFZ is leading or very actively contributing to eight international services of the IAG with highest visibility and impact and cooperates with many international partners (GRACE-FO Science Data System, European GRACE-FO Science Team) in analyzing the available data. AWI and GFZ are main contributors to the development of new national satellite missions (EnMAP, TANDEM-L) and algorithm development for national and European Sentinel and other ESA missions. Modeling activities benefit from strong strategic partnerships as established, for example, through the DRAKKAR project (scientific and technical planning) and involvement in the ExtremeEarth consortium (making models and associated workflows exascale-ready).

Risks and Opportunities. Improving and implementing state-of-the-art sensors, observation platforms and robotic technologies is very costly and needs coordinated strategic investment, and national as well as international partnerships. A proposal has been submitted for realizing this task to the Helmholtz Strategic Investment program (MUSE; see Ch. 1.4.2). The realization of a next-generation MCM, for which a strategic investment proposal is planned, would be an opportunity to apply space-based quantum sensors, to increase spatial and temporal resolution, and to improve understanding of how anthropogenic climate change and natural climatic cycles interact. However, the success (scheduling, data accuracy) of a satellite mission is always subject to various uncertainties and a delay of the launch of the MCM cannot be excluded. Developing new proxies based on seawater distributions of metals and their isotopes always bears the risk of alterations upon incorporation into paleo-oceanographic archives, which will be reduced by systematic surface sediment and culture studies, as well as through signal modeling and statistical deconvolution. Future exascale computers provide the opportunity to push the boundaries in high-resolution Earth system modeling. However, making Earth system models and associated workflows exascale-ready provides a formidable challenge that will be tackled.

E) Subtopics

Expertise and preliminary work. Based on close cooperation between observational, paleo proxy and modeling experts, there is a strong track record of achieving and applying new process understanding to improve models such as high-resolution sea ice-ocean and climate models.[71]

Paleoclimate and paleo-oceanographic research has been particularly successful in the development of new proxies[72] and their application to marine and high-resolution lake sediment and ice cores for detailed environmental reconstructions, including all aspects of the global ocean overturning circulation systems on a broad range of time scales.[73] Researchers in T2 are international leaders in obtaining such records and in exploiting them to advance system understanding. The interpretation of proxies by means of Earth system modeling has been another successful area of research. Scientists in T2 have also been actively engaged in the investigation of variability and extreme events including their reconstruction from instrumental and proxy records,[74] modeling, and the development of statistical reconstruction methods.[75]

By implementing long-term observations in key regions of the Atlantic thermohaline and wind-driven circulation, improved understanding of natural variability in the ocean and its response to climate variability has emerged. Advanced knowledge on the mechanisms of climate variability from interannual to millennial time scales and their linkages between polar regions, mid-latitudes and tropical regions has been achieved.

Determining limits of predictability and contributing to actual predictions on daily-to-decadal time scales is another relevant field of research, in which expertise is available[76,77] that will be further developed in T2.

T2 scientists also have extensive experience in research related to global and regional sea level change and its underlying causes. Examples include ice sheet dynamics, ice shelf-ocean interaction, ocean circulation changes, sea level observations, self-gravitation, Solid Earth dynamics as well as the quantification of ice and ocean mass redistribution, e.g., by means of satellite gravity missions (GRACE, GRACE-FO).

T2 scientists have a strong track record in developing advanced research methodologies including new observational capacities, novel remote sensing algorithms, novel proxies for past sediment and water properties[78] that are developed and calibrated based on water column distributions such as obtained in the frame of the international GEOTRACES program, as well as in the emerging field of artificial intelligence.[79] Modeling is another strength of the participating partners, especially for (regionally) high-resolution simulations, data assimilation and bringing different Earth system components together. Contributions to CMIP6, including various MIPs, demonstrate the ability to turn modeling into societally relevant outcomes.

A world-leading infrastructure enables the proposed science. For example, icebreaker RV Polarstern is arguably the most capable polar research vessel in the world. Large infrastructure investments such as FRAM, MOSES, ACROSS allow to apply cutting-edge observing techniques with innovations in temporal and spatial resolution, as well as in enabling long-term observation in challenging environments such as under ice and in the deep sea. Scientists of T2 are strongly involved in several Earth observation satellite missions (e.g., GRACE-FO, SWARM), operate a satellite receiving station, the altimetry ground-truthing facility at Lake Issyk Kul (Kyrgyzstan), a satellite laser ranging station in Potsdam, and GNSS and tide gauge stations in various parts of the world. Further sup-

[71] *Lüpkes C, Gryanik VM. 2015. A stability-dependent parametrization of transfer coefficients for momentum and heat over polar sea ice to be used in climate models. JGR: 120.

[72] *Bertlich J, et al. 2018. Salinity control on Na incorporation into calcite tests of the planktonic foraminifera Trilobatus sacculifer–Evidence from culture experiments and surface sediments. Biogeosciences. 15:5991–6018.

[73] *Lembke-Jene L, et al. 2018. Rapid shift and millennial-scale variations in Holocene North Pacific Intermediate Water ventilation. PNAS. 115:5365–5370.

[74] *Rimbu N, et al. 2016. Atmospheric circulation patterns associated with the variability of River Ammer floods: evidence from observed and proxy data. Climate of the Past. 12:377-385.

[75] *Münch T, Laepple T. 2018. What Climate Signal Is Contained in Decadal- to Centennial-Scale Isotope Variations from Antarctic Ice Cores? Climate of the Past. 14:2053–2070.

[76] *Zampieri L, et al. 2018. Bright Prospects for Arctic Sea Ice Prediction on Subseasonal Time Scales, GRL. 5:9731–9738.

[77] *Kushnir Y, et al. 2019. Towards Operational Predictions of the Near-Term Climate, Nat Clim Change Perspectives. 9:94–101.

[78] *Maier E, et al. 2018. North Pacific freshwater events linked to changes in glacial ocean circulation. Nature. 559:241–245.

[79] *Irrgang C, et al. 2019, Estimating ocean heat content from tidal magnetic satellite observations. Scientific Reports. 9:7893.

port is provided by state-of-the-art laboratories, analytical infrastructure (ST2.4), research aircraft and excellent research stations in the Arctic, Antarctic and the tropics, as well as high-performance computing facilities.

Scientists in T2 also have a long experience in agenda setting and coordination of major large-scale projects. Prominent examples include ADVANTAGE and CTA ESM (Helmholtz Association), PalMod and NEROGRAV (national), AtlantOS/EuroSea, APPLICATE, Beyond EPICA (Europe) as well as MOSAiC, the Year of Polar Prediction (YOPP), ICDP/IODP and several WCRP activities (international).

Finally, T2 can rely on strong knowledge transfer activities that were established and expanded during PoF III. The Climate Office and the Arctic Office hosted by AWI, as well as the Gravity Information Service (GravIS) hosted by GFZ are prominent examples. Furthermore, AWI and GEOMAR scientists play a leading role in climate policy for UNFCCC (e.g., UN Decade of Ocean Science for Sustainable Development) and have actively contributed to past and forthcoming IPCC reports.

Uniqueness. The T2 consortium, along with their strategic partners, provides the expertise and critical mass to achieve major scientific advances of societal relevance. T2 scientists rely on a unique portfolio of modern research infrastructures such as research vessels, aircraft, satellites, research stations, laboratories, observation platforms and high-performance computers. Furthermore, by bringing together experts from three centers – combining know-how in observations, remote sensing, theory, modeling and data science – T2 scientists will be able to tackle scientific challenges that require a systems approach. In-house expertise in modeling along with critical strategic partnerships will ensure that new knowledge will be implemented in models, thus providing a direct way to enhanced prognostic capacity relevant to society. T2 also benefits from well-established knowledge transfer activities that are closely tied to the research activities. The availability of long-term funding through the Helmholtz Association is another strength that allows us to address challenges that require concerted efforts over sustained periods of time.

F) Collaboration and transfer

Partners. T2 has strong strategic ties to well-established regional networks. At the national level, beyond multiple ties to local universities, strategic partnerships are reflected by large-scale projects such as those funded by the BMBF (e.g., PalMod, SPACES, ROMIC) and the DFG (e.g., SPP Sea Level, TRR Arctic Amplification). Important partners at the national level include the Max Planck Institutes for Meteorology and Chemistry, the German Climate Computing Centre (DKRZ[80]) and DLR. Furthermore, T2 scientists team up with strategic partners at the European level through various projects and coordinated activities (e.g., AtlantOS/EuroSea, APPLICATE and Beyond EPICA) and through partnership with the European Space Agency and ECMWF. High-profile international partners also include NASA for the operation of the gravity mission GRACE-FO and the planning of the next generation MCM as well as AARI (St. Petersburg) for Arctic research and the Qingdao National Laboratory for Marine Science and Technology.

Positioning of the Topic in international research. T2 scientists have a track record in shaping, coordinating and contributing to major national, European and global projects that combine complementary expertise for solving major scientific challenges (see previous section). Strategic partnership at the international level is established through programs such as WCRP, WWRP, IODP, GCOS, WGMS and GGOS. This strategy will continue to be pursued in PoF IV given that it allows bringing together of strategically relevant players in the field (see partners mentioned above) while exploiting complementarity in expertise and activities.

Cross-Topic and Cross-Cutting Activities and Alliances. For T2, CARF REKLIM will play a critical role in bridging research activities on present and future sea level change, as well as for analyzing extreme events and abrupt climate transitions. T2 also benefits from REKLIM's well-established knowledge transfer activities. T2 scientists are actively engaged in CARF HI-CAM, especially in the part on adaptation to European extreme events such as heatwaves and droughts. T2 provides knowledge of drivers related to jet stream changes and storyline scenarios to the impact modelers.

[80] AWI is a shareholder of DKRZ (9% share).

CTA ESM provides a cornerstone of the Earth system modeling activities within T2. This includes coordination of modeling activities among different Topics, technical work such as the coupling of new subsystems, the development of new components and coupled data assimilation capacities, a common modeling infrastructure that will be used by all contributing centers (ESM-Tools), as well as coordinated frontier simulations. Through CTA ESM, T2 is actively engaged in developing a common national modeling strategy. CTA MOSES plays an important role for T2 in terms of developing modular ocean observing systems to determine the role of meso-scale ocean eddies in climate. CTA DE will provide methods and applications from AI to develop observation strategies and data exploration/sharing capabilities (also for knowledge transfer).

T2 is strongly engaged in two more CARFs, namely JL Exascale Earth System Modeling (JL-ExaESM) and Remote Sensing. With JL-ExaESM, the RF E&E, RF Information and RF Aerospace, Space and Transport explore specific concepts to enable exascale readiness of Earth system models and associated workflows, leveraging co-design between domain and computer scientists to address the computational and data challenges posed by future supercomputers. Remote Sensing is important for developing new methods for process understanding of ice sheets and glaciers, sea ice and permafrost. It will provide a unique opportunity to combine expertise in the material properties of glaciers with the new radar satellite-borne techniques developed at DLR. From workflows of big data in remote sensing to polarimetric radar studies, links in many specific themes between the institutes are fostering the understanding of cryospheric processes.

T2 also exploits activities established in the context of the Helmholtz Incubator ‘Information and Data Science’. Prominent examples include the Helmholtz School for Marine Data Science (MarDATA), which aims to define and educate a new type of ‘marine data scientists’ by introducing and embedding researchers from computer sciences and mathematics into ocean sciences, covering a broad range of themes including supercomputing and modeling robotics, as well as big data methodologies and the RF E&E Metadata Hub (Incubator).

T2 has very close links to other Topics in strategically relevant themes. Extreme events will be considered in close collaboration with T1. This includes drivers of change and teleconnections (e.g., Arctic sea ice, stratosphere or El Niño). There is also a strong link to T4 for studying coastal sea level change. In this context, concrete measures fostering collaboration include sharing of infrastructure involving cross-scale observing systems (e.g., tide gauges, altimetry), provision of boundary conditions from global simulations to coastal models and identification of focal areas (Northeast Atlantic, Southeast Asia). Close collaboration with T6 is envisaged in three main themes, namely the fate of life in sea ice, carbon fluxes in the ocean as well as changes in ocean biogeochemistry, ecosystems and biodiversity. It is planned to initiate a further CTA in the Program focusing on climate thresholds and the dynamics of carbon sources and sinks.

Transfer and contribution to SynCom. One important strategic element of T2 will be the science-enabled transfer of knowledge based on an outcome-oriented research agenda along with a dedicated stakeholder dialogue (e.g., stakeholder conferences, tailored information products, web information systems), which will be coordinated amongst others by the Climate Office, Arctic Office and REKLIM. At the same time, visibility of knowledge transfer activities will be supported by a strong science-oriented communication, addressing various stakeholder groups and the wider public. Furthermore, the focus on extreme events will be of high relevance for decision-makers. With its scientific results and numerical experiments (CMIP), T2 will also contribute to future IPCC assessment reports, addressing critical knowledge gaps (e.g., polar sources of sea level rise, natural climate variability).

T2 can build on a wide range of successful activities from policy advisory services (e.g., Arctic Office, IPCC Office) and dialogue platforms (e.g., Arctic dialogue, meereisportal.de, polar prediction blog) over the provision of data analysis tools (e.g., PDAF) to prediction methods (e.g., sea ice outlook). In addition, the establishment of innovative educational opportunities is envisaged (e.g., interactive course format ‘climate change and its impacts’ in adult education in community colleges on the national level as 'education for participation' through REKLIM and the Climate Office in collaboration with WWF).

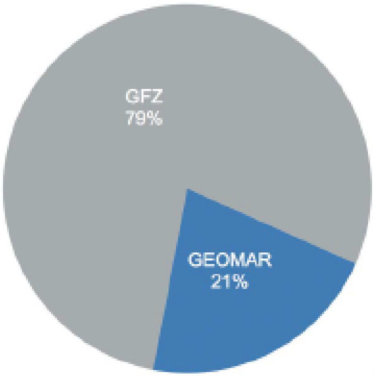
Knowledge transfer in T2 will also be strengthened through partnerships. Within the RF E&E active contributions to and support by SynCom will be an important strategic element. This includes the dialogue with stakeholders and the public, responding to acute demand and crises, synthesis and foresight processes, and communication. At the national level, T2 will team up with partners under the umbrella of the Deutsches Klima Konsortium (DKK), Deutsche Allianz für Meeresforschung (DAM) and the German Marine Research Consortium (KDM) to maximize and improve its service to society (e.g., through provision of joint brochures such as the one recently produced on the Gulf Stream). Finally, stakeholder networks in the context of European projects such as AtlantOS/EuroSea or the Arctic European Cluster will be exploited. Across all partnership dimensions, close collaboration with operational centers for transferring research into operations will be key.

Executive Summary

- T2 teams up to close critical knowledge gaps in our understanding of the ocean and cryosphere and their role in the climate system, building on long-term monitoring, observations, process understanding, and modeling. Research focuses on the drivers of global and regional climate change, variability and extreme events and their impacts with emphasis on ice sheets and sea ice, sea level as well as ocean temperatures and circulation. Thereby, the prognostic capacities from the poles to the tropics and from daily to millennial time scales will be advanced.
- From an ocean and cryosphere perspective, T2 addresses global and regional climate change, extreme events (e.g., HI-CAM) and their modeling and predictability (with T1, T4, T6). T2 contributes to research on biogeochemical cycles and ecosystems (with T6), terrestrial processes such as permafrost thawing and droughts (with T5), as well as impacts of sea level changes on coasts (with T4).
- T2 focuses on drivers and impacts of natural and anthropogenic changes of the ocean and cryosphere as integral components of the climate system directly affecting society. T2 will contribute basic knowledge and science-based scenarios to inform adaptation and mitigation measures in the context of the 2030 SDG Agenda and the Paris Climate Agreement.

Topic 3: Living on a Restless Earth: Towards Forecasting Geohazards

Spokesperson: Fabrice Cotton GFZ; Deputy: Colin Devey, GEOMAR



The mission of Topic 3 is to develop the next generation of observation systems and interpretation and modeling framework in order to provide robust and innovative methods for long-term hazard assessments and short-term forecasting of the most threatening geohazards. This will involve expanding our knowledge of the drivers of the relevant physical processes (including the contribution of climate change), with a major focus on identifying, understanding, and exploiting the build-up phases of hazardous events, such as earthquakes or volcanic explosions, as well as multi-hazard cascade processes. We will evaluate the impacts of extreme events on 21st-century society, considering urban planning, early warning and rapid response systems.

A) Scope and challenge of the Topic

Research subject. While hazards are inevitable, the worst of their consequences are not: loss of life and infrastructure can be minimized through monitoring and modeling. Looking ahead to the next decade and beyond, geohazards studies will expand substantially and face key challenges, namely: i) The effects of geohazards (e.g., earthquakes, volcanic eruptions, tsunamis, rapid erosion, and submarine and subaerial landslides, Fig. 3.1) will be increasingly deadly, costly, and disruptive for our urban and high technology societies as well as for rapidly growing megacities worldwide. ii) New hazards such as 'space weather'[81] or geohazards caused or triggered by land use and underground activities (e.g., fluid withdrawal or injection) are causing new threats. iii) Recent events show that geohazards may be coupled through dynamic interactions that need to be better understood,[82] requiring improved means of risk communication. iv) The impact of climate change (e.g., changes in extreme precipitation events and their impact on landslide hazard) must be addressed. v) With the acquisition of increasing quantities of monitoring data and the development of information technologies, the public and decision-makers increasingly expect rapid, transparent, and reliable warning and information.

[81] Space weather is a collective term used to describe hazardous events in the near-Earth space environment that can have an effect on humans and technology in space and can have adverse effects on the ground.

[82] The Palu earthquakes and Anak Krakatau volcanic eruption triggered mass movements that were not detectable by classical tsunamis early warning systems 'Tsunamis Revisited', editorial (2019), Nature Geoscience. 12:149.

In order to address these challenges, Topic 3 (T3) will expand and develop new methods for assessing, simulating, and forecasting[83] geohazards through an even stronger multi-disciplinary research approach (as recommended during the PoF III evaluation). These will be integrated into efforts to gain a greater understanding of the geological, geochemical, and geophysical processes that lead to such events, including their probability, magnitude, and extent. Our research strategy will have a particular focus on urban areas and the land-sea interface, where the largest geohazard-related disasters have occurred during the last decade.

The scope of our investigations should consider the entire planet Earth: the surface and near-surface geology which controls hydrology and geomorphology, the crustal and mantle interactions that control tectonic stress and drive lithospheric plates and volcanism, and the core, the source of the geomagnetic field which interacts with the solar wind. Our research needs to cover all time scales, from seconds to hours (landslides, earthquakes, tsunamis), days to years (volcanic eruptions), and years to millions of years (e.g., crustal motion), while the recurrence rates of the events of concern range from months to thousands of years.

Explanation and justification of research. About 2.7 billion people (1/3 of the global population) are exposed to earthquake hazards, and more than 700 million live near dangerous volcanoes. Extremely large (in terms of the magnitude of the event or impact on society) geohazard events pose a serious challenge to the global community. This is exemplified by the cascading effects of the 2011 Tohoku earthquake, which triggered a devastating tsunami that damaged the Fukushima nuclear power plant, as well as causing volcanic unrest, numerous landslides, and water level changes in aquifers thousands of kilometers distant. Such events can have **far-reaching societal effects around the world**; for example, the Fukushima disaster led to the political decision to end nuclear power production in Germany by 2022.[84] Furthermore, **climate change and human activities exacerbate some geohazards**, e.g., increased landslide susceptibility due to deforestation, or induced seismic events triggered by the injection of fluids during shale gas or geothermal production.[85] Finally, society's reliance on **high-technology infrastructure increases its vulnerability to geohazards**. For example, even small volcanic eruptions can severely disrupt air traffic (e.g., the 2010 eruption of Eyjafjallajökull in Iceland[86]), while ionizing radiation from geomagnetic storms can harm satellites.

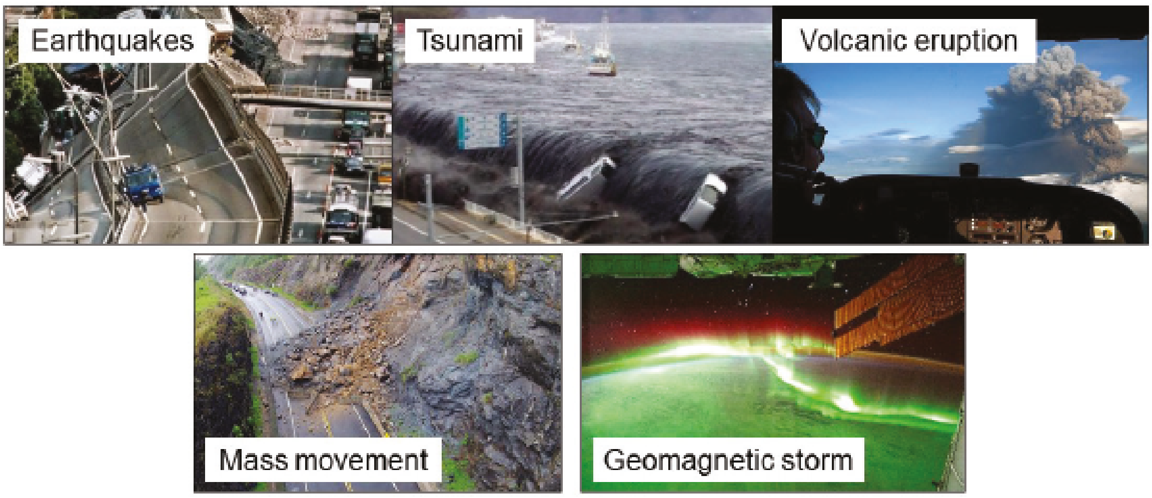


Fig. 3.1: Examples of the geohazards and their impacts that will be addressed in Topic 3.

[83] Forecast refers here to a "definite statement or statistical estimate of the likely occurrence of a future event or conditions for a specific area". 2009 UNISDR Terminology on Disaster Risk Reduction, UNISDR-20-2009-Geneva.

[84] https://www.dw.com/en/german-cabinet-approves-2022-nuclear-shutdown/a-15134028-1

[85] *López-Comino JA, et al. 2018. Induced seismicity response of hydraulic fracturing: results of a multidisciplinary monitoring at the Wysin site, Poland. Scientific Reports. 8:8653.

[86] Sanderson K. 2010. Questions fly over ash-cloud models. Nature. 464:1253.

The Topic's outcomes are, therefore, foreseen to be exploited by relevant stakeholders. Model simulations will be used to evaluate the potential impact of geohazards, while the inferred **scenarios** and associated **improved awareness** of hazard potential will be communicated using such means as hazard maps, risk[87] models, and early warning and rapid response systems. These outcomes will provide valuable support for urban planners, civil protection agencies, infrastructure operators, and insurance companies in their efforts to mitigate against such events, including the assessment of their potential costs.[88]

Strategic guidelines (FoPoZ). Solutions to pressing societal problems are at the core of the PoF IV program objectives. The essential role of T3 lies in enhancing our understanding of the **processes that cause geohazards**, by **assessing** and **forecasting geohazards**, including those enhanced by climate change, and by improving on how these outcomes are transferred to **practical mitigation actions** in order to enhance society's resilience. This is especially relevant for **urban areas**, since research into urban spaces is being taken into account across the entire program. T3 will assess impacts and adaptation to extreme events, and contribute to the development of science-based options for actions and services. In accord with the policy guidelines and in coordination with other Topics, T3 will develop and expand **observation and monitoring systems** in the oceans, on land and in orbit (sea-land-space). These activities will be underpinned by advancements in geoinformation systems and data infrastructures, exploiting advances in **artificial intelligence (AI) and big data science** (e.g., Digital Earth[89]).

Internationalization will be advanced by leadership in various research programs (e.g., Plate Boundary Observatories crossing the sea-land transition, new urban monitoring systems, Earth surface process observatories, laboratory activities). It will be supported by the provision of **multidisciplinary and multi-sensor integrated datasets**, which are necessary at the international level to tackle key global challenges, while **international scientists** will be encouraged to collaborate with our scientists and take advantage of the leading-edge analytical and experimental infrastructure. An example of the Topic's contribution within an international context is how it will advance the United Nations **Sendai Framework for Disaster Risk Reduction** 2015–2030,[90] discussed below.

The **digitalization** strategy will focus on real-time (or rapid) and user-friendly data access, while data interoperability will facilitate the interface between data acquisition systems and databases with high-performance computing (HPC) platforms dedicated to datamining and model assimilation. Interactions with industry (e.g., insurance institutions, the support of start-ups) will benefit from knowledge and technology transfer specialists at the participating centers.

Function and contribution of the Topic within the Program. T3 is dedicated to understanding geodynamic processes and multiple geohazards, two fields closely linked to almost all other Topics (Fig. 3.2).

- There will be strong interactions between T3 and T8. Earth system processes that drive geohazards are often related to the formation of georesources, e.g., geothermal energy and metallic raw material resources are commonly related to volcanism, while fluid injections or extractions related to subsurface utilization may induce/trigger seismicity.[91] Furthermore, identifying suitable areas for the safe storage of high-level radioactive waste requires specific geohazard studies. Also, gas-hydrate research is at the interface of T3 and T8, since gas-hydrates are both a potential energy resource and with their instability, a possible cause of submarine landslide hazards.

[87] Note that hazard and risk are related by the schematic equation H x E x V = R, where H is the hazard or consequence of an event (e.g., ground shaking due to an earthquake), E is the exposure, i.e., how many buildings, the population, etc., V is the vulnerability, meaning how a structure responds to a given input, i.e., how damaged a type of building is due to an given ground motion), and R is the risk or consequences of the event in terms of losses and fatalities.

[88] *Kreibich H, et al. 2014. Costing natural hazards. Nat Clim Change. 4:303–306.

[89] See https://www.digitalearth-hgf.de/.

[90] See https://www.unisdr.org/we/inform/publications/43291.

[91] *Kwiatek GF, et al. 2019. Controlling fluid-induced seismicity during a 6.1-km-deep geothermal stimulation in Finland. Science Advances. 5(5):eaav7224.

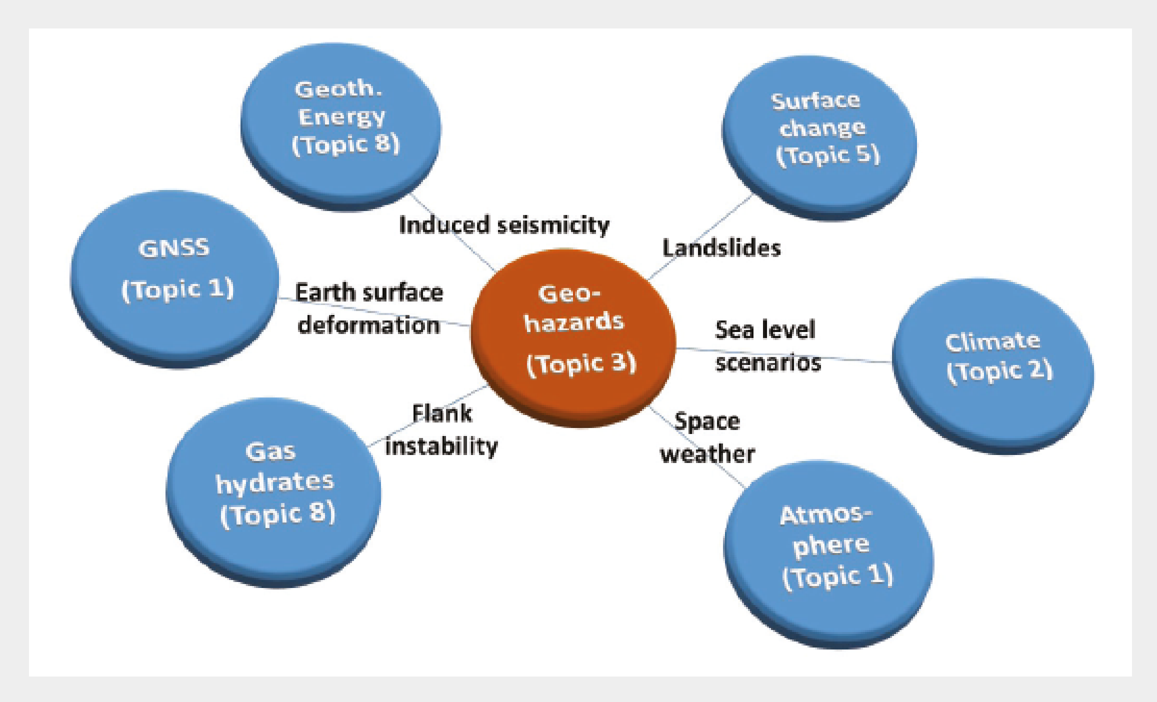


Fig. 3.2: Examples of major thematic-driven links between T3 and others.

- Increasing erosion due to landslides,[92] the perturbation of the Earth's surface by earthquakes, and increased susceptibility to mass-movement (rockfalls, debris flows, and landslides) due to climate change (e.g., extreme rain events) motivates interactions with T5 to enhance our understanding of Earth surface processes. This also requires the study of atmosphere/surface interactions, leading to links with T1 and T2.
- GNSS (i.e., GPS, GLONASS, BeiDou and Galileo) atmospheric monitoring (T1) will improve the corrections required for more precise plate motion monitoring. The analysis of extreme space weather events will also be shared with T1 since the atmosphere and near-Earth space sources of the Earth's magnetic field are crucial when constraining variations in the geomagnetic field and vice versa.
- The issue of extreme events is of concern to T2 (role of the ocean in the climate), T4 (coastal transition zones), and T5 (floods), leading to a strong mutual interest in how climate change and extreme geohazards events interact.

Highlights.

T3 plans to undertake a broad systems research program focusing over geohazard on different scales, from material sciences to applied science, from the atomic scale to the global scale. T3, via its monitoring program, will acquire, integrate, and exploit long time series of **sea-land-space** observations. This information, when coupled with innovative data mining strategies, will provide an **unprecedented potential to detect changes** that deviate from the background signals. These results, in turn, will be combined with advanced modeling schemes to evaluate if such changes are indicative of a forthcoming event, leading to new paradigms for geohazard forecasting.

T3 will develop monitoring and research strategies that are adapted to, and take advantage of, **urban environments** (e.g., the use of fiber optics networks or crowdsourced data). Geohazards forecasts will **be integrated into early warning systems or urban risk models that take into account advanced infrastructure**, on land and in near space.[93] These activities will provide a valuable contribution to, and benefit from, the activities associated with CARF Resilient Urban Spaces.

[92] *Emberson R, et al. 2016. Chemical weathering in active mountain belts controlled by stochastic bedrock landsliding. Nature Geoscience. 9:42–45.

[93] *Shprits Y, et al. 2018. Discussions on stakeholder requirements for space weather-related models. Space Weather. 16(4):341–342.

B) Main research and structural objectives

Research Objectives.

- **Objective 1: To understand why and where geohazards are occurring by the analysis of their drivers.** This requires the unique set of multidisciplinary competences and research facilities provided by the involved institutes to study the fundamental processes and interactions between the components of the Solid Earth system. Our goal is to evaluate the combinations of conditions that lead to the most serious, and subsequent cascading, events.
- **Objective 2: To detect changes in the Solid Earth system over various temporal and spatial scales.** Use will be made of observables from land-sea-space monitoring networks and innovative data-mining strategies. The ultimate goal is to evaluate if and how the preparatory phases of catastrophic events can be detected and integrated into warning systems and time-dependent hazard assessments.
- **Objective 3: To characterize, understand, and model past, present, and future extreme and high impact events.** Archives of previous events will be reviewed, and new approaches developed to forecast cascade effects and possible 'black swan' events (those that come as a surprise and have a major effect). As in Objective 2, these will be incorporated into appropriate mitigation strategies.
- **Objective 4: To develop a shared vision of the unexpected to improve preparedness.** The communication and transfer of knowledge between the geoscientific and decision-making communities will be improved, including developing **scenarios** of future events and disseminating the potential associated losses, innovative training programs, and the development of citizen science and crowdsourcing methods.[94] The final goal is having **appropriate authorities being better prepared for future extreme destructive events.**

Structural Objectives.

- **Objective 5: Establishment of a globally unique onshore-offshore monitoring framework.** The integrated marine/terrestrial expertise of the members of the Topic partners will allow such a framework to be implemented, as recommended by the PoF III evaluation report.
- **Objective 6: Establishing a framework for the distribution of observations and model simulations to the global geoscience and stakeholder communities in a free and open manner.** T3 will take advantage of developments in big data by establishing the means of distributing the acquired observations and model simulations to the wider scientific community as effectively as possible. The development of innovative deep learning methods and the encouragement of community or citizen science initiatives will be major contributions of T3 to SynCom.

C) Structure of the Topic and motivation of Subtopics

Introduction of Subtopics. Each of the four research objectives is linked to a Subtopic (Fig 3.3). We will work towards a better comprehension of the fundamental mechanisms behind the processes driving geohazards (Subtopic 3.1) via the identification of temporal variations in observables and the later stages before catastrophic events (Subtopic 3.2), the improved understanding of extreme and high-impact events (Subtopic 3.3), and the translation of the new knowledge to mitigation efforts and its communication to stakeholders (Subtopic 3.4).

Contributions of the Centers to the Topic. The participating centers have **internationally recognized expertise** in virtually all fields of the Solid Earth system sciences and their integration for exploring the processes addressed in this Topic. This is coupled with world-class expertise in the imaging of the subsurface over scales ranging from the upper mantle, lithosphere, and crust to the detailed near-surface structure. This combination

[94] Zheng F, et al. 2018. Crowdsourcing methods for data collection in geophysics: State of the art, issues, and future directions. Reviews of Geophysics. 56:698–740.

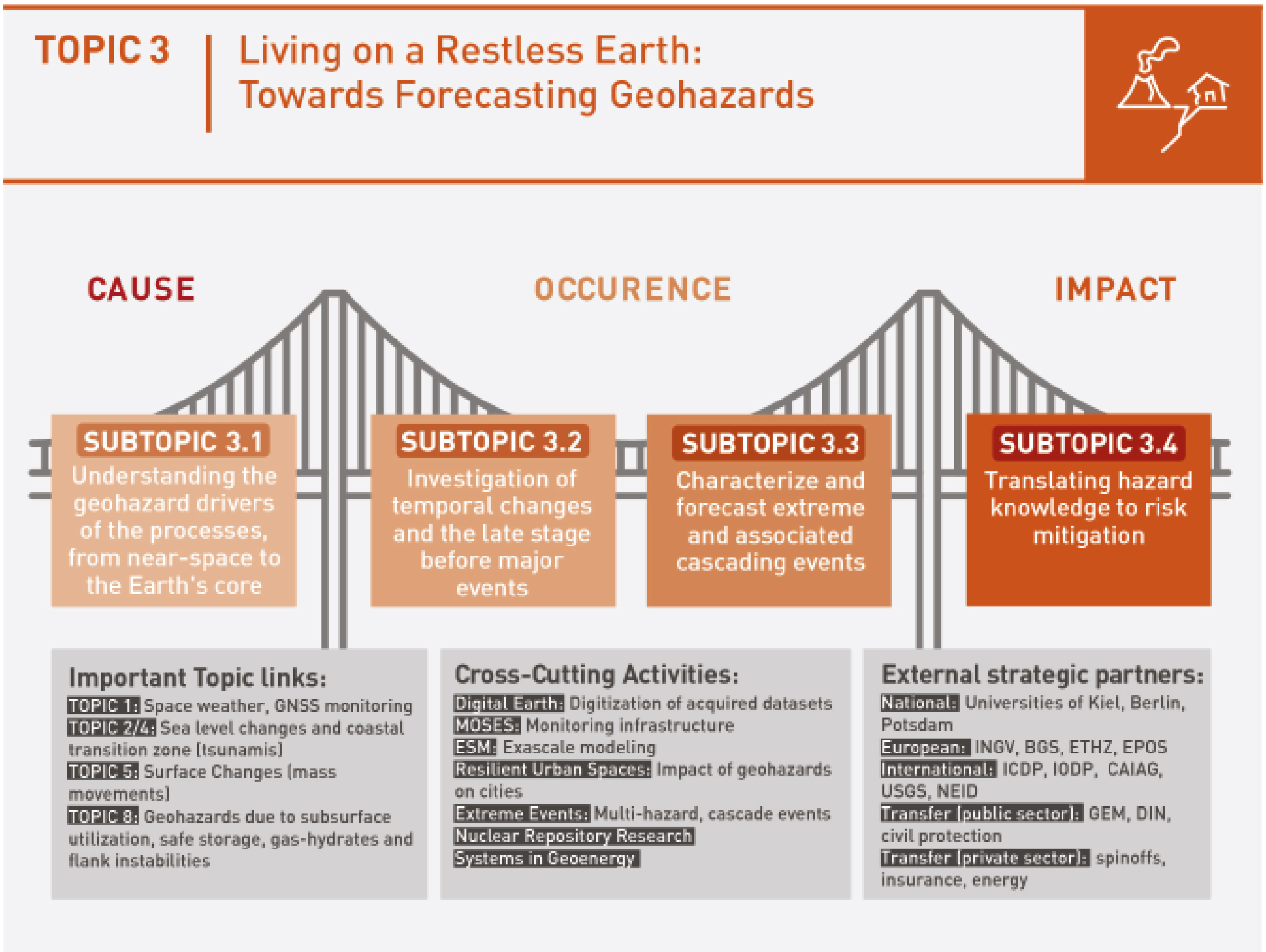


Fig. 3.3: The holistic route from the drivers of geohazards to their impact.

of data acquisition capacity and process-related **fundamental and applied research** is the defining strength of T3. The key elements supporting T3's research are the long-term Plate Boundary Observatories (PBOs) developed over the last decade (e.g., at the North Anatolian fault, Northern Chile), global networks for seismic monitoring (e.g., GEOFON[95]), and stations for monitoring the Earth's magnetic and gravitational fields. The global scope is further supported by **satellite missions** (GFZ is a principal partner of GRACE-FO, Gravity Recovery and Climate Change Experiment[96] and is involved in SWARM[97]), as well as GNSS and satellite radar (e.g., InSAR applications for measuring surface deformation). Critical for land-sea observations are marine research vessels (GEOMAR will coordinate the vessel to replace the Poseidon and Meteor). Finally, both GFZ and GEOMAR operate a number of **state-of-the-art analytical and experimental laboratories** (e.g., for bulk sample and in situ geochemistry and geochronology) and have extensive experience in the development of **innovative modeling and data analysis tools**. An example of how all of this infrastructure will be exploited is the GFZ MESI (Modular Earth Science Infrastructure[98]) framework, which covers the overall management of the space systems, global observatory networks, key laboratories, and a mobile geophysical instrument pool (see Ch. 14).

[95] See https://geofon.gfz-potsdam.de/.
[96] See https://www.gfz-potsdam.de/en/section/global-geomonitoring-and-gravity-field/projects/gravity-recovery-and-climate-experiment-follow-on-grace-fo-mission/.
[97] See https://www.gfz-potsdam.de/en/section/geomagnetism/infrastructure/swarm/.
[98] See https://www.gfz-potsdam.de/en/scientific-infrastructure/research-infrastructures/.

D) Subtopics

Subtopic 3.1 The drivers of geohazards

Christian Berndt, GEOMAR; Sascha Brune, GFZ

Scope and challenges. The teams in Subtopic 3.1 will explore the multi-scale coupling of the various Solid Earth system processes and their interactions with the surface and surrounding space. This will involve studies such as linking core/mantle convection with lithospheric deformation and crustal processes,[99] including their observable expressions in the surface geology (orogeny, basin formation, faulting, magmatism, uplift, and erosion) and beyond (the geomagnetic field). Laboratory facilities will be expanded to study the physical-chemical properties of relevant Earth materials under representative conditions, along with the deployment of multi-sensor networks to gain high-resolution time-series data on geodynamic processes (e.g., plate motion and deformation, thermal and stress fields) in specific regions and at global scales. Finally, innovative models and data assimilation methods will be developed to better understand Earth system interactions. The key challenge faced is the enormous spread of the spatial and temporal scales involved, ranging from seconds to millions of years and from millimeters to thousands of kilometers.

Main objectives. The research in this Subtopic involves a multidisciplinary analysis of the physical, chemical and rheological properties of the Earth, and its current and past states with respect to its geodynamic settings. The aim is to distinguish between a geosystem in equilibrium or steady state from one approaching instability, thus triggering extreme events. Ultimately, we seek to quantify the thresholds and transitions towards instability as input to ST3.2 and ST3.3.

Work program. Subtopic 3.1 is organized into four themes (Fig. 3.4).

Material properties. Novel analytical, experimental and modeling techniques will be employed to key sample suites (including deep boreholes from the International Continental Drilling Programs – ICDP and the Integrated Ocean Discovery Program – IODP) in order to elucidate the chemical, mechanical and thermal properties of crustal and mantle minerals and rocks. Examples include mineral phase transitions that can drive deep earthquakes, the genesis of geofluids by melting or devolatilization reactions, the variability of fault and material properties at subduction megathrusts,[100] and the erodibility of exposed rocks.

Structures, fluids, magmas and magnetic/gravity fields. In order to image the present-day state of the Earth's crust, mantle, and core, dedicated geochemical, seismological, gravity, and electromagnetic surveys using land-, ocean-, and air-based sampling and observatory networks will be undertaken in selected focus sites, including those in Chile, Mt. Etna in Sicily, the North Atlantic and its volcanic islands (including Iceland), the Kurile-Kamchatka-Aleutian Arc system, and the new Eifel observatory (Germany). These will use mobile instrumentation from the GIPP (Geophysical Instrument Pool Potsdam). The current permanent global networks of seismic and geomagnetic stations will be maintained and upgraded, while the temporal variation in the Earth's gravity and magnetic fields will be defined through satellite-based platforms, all operating as modules of MESI.

Temporal Evolution. The short- (human time scale) and long-term (geological scale) evolution of Earth's internal structures, processes, and their surface expressions will be inferred. This will involve geophysical experiments, geochemical and mineralogical analysis of geological archives,[101] mapping of past and present deformation patterns and resolving the current and past stress states of the Earth's crust. Changes in the Earth's magnetic field will be monitored to gain information on deep-earth processes, while also assessing hazards associated with the solar wind. Special attention will be paid to quantifying and modeling geofluids through the crust, as well as on the surface, given their role in nearly all geohazards (earthquakes, volcanic hazards, landslides[102]).

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[99] *Kind R, Yuan X. 2010. Geophysics. Seismic images of the biggest crash on Earth. Science. 329(5998):1479–80.

[100] *Moreno M, et al. 2018. Chilean megathrust earthquake recurrence linked to frictional contrast at depth. Nature Geoscience. 11(4):285.

[101] *Hoernle K, et al. 2015. How and when plume zonation appeared during the 132 Myr evolution of the Tristan Hotspot. Nature Comm. 6:7799.

[102] *Elger J, et al. 2018. Submarine slope failures due to pipe structure formation. Nature Comm. 9(1):715.

Processes. The complex links between material properties, geological structures, geofluids, and their temporal evolution can only be understood within a multidisciplinary framework where observational, analytical, and experimental studies (themes 1–3 above) are combined with cross-scale modeling and data integration. Thus, a variety of modeling tools will be developed and improved including; mantle and core convection simulations, cross-scale lithosphere deformation and surface processes, atomistic numerical and elasto-gravitational wave simulations, and space weather models that reproduce the dynamics of energetic particles in the near-space environment.[103] These large-scale and long-term models of geoprocesses are needed to constrain the initial and boundary conditions for more specific concept models of resource formation and reservoir simulations in T8.

Deliverables (D) and Milestones (M)

- **D3.1 (2027):** 4D-integration of multidisciplinary subsurface imaging with geomaterial properties. **M3.1-1 (2022):** Deployment of dense sensor networks for high-resolution imaging of the crust at key sites in order to analyze the drivers of deformation and seismicity. **M3.1-2 (2023):** Establishment of a platform for geodynamic, volcanological, and geochemical data sharing and integration (including establishing a core log seismic integration research center). **M3.1-3 (2025):** Development of empirical relationships between geological case studies with experimental/atomistic investigations to quantify the key properties of Earth materials and their response to changing geodynamic conditions.
- **D3.2 (2027):** Quantification of the key dynamic instabilities of the Solid Earth system. **M3.2-1 (2024):** Development of exascale modeling methodologies to simulate thresholds and transitions towards instabilities in the Earth's subsystems (e.g., earthquake cycles, particle populations in the inner magnetosphere, volcanism, and volatile release processes at plate boundaries). **M3.2-2 (2025):** Reconstruction of multi-parameter (time-composition-magnitude) records of volcanic activity, their cycles, and inferred trends for key study areas.

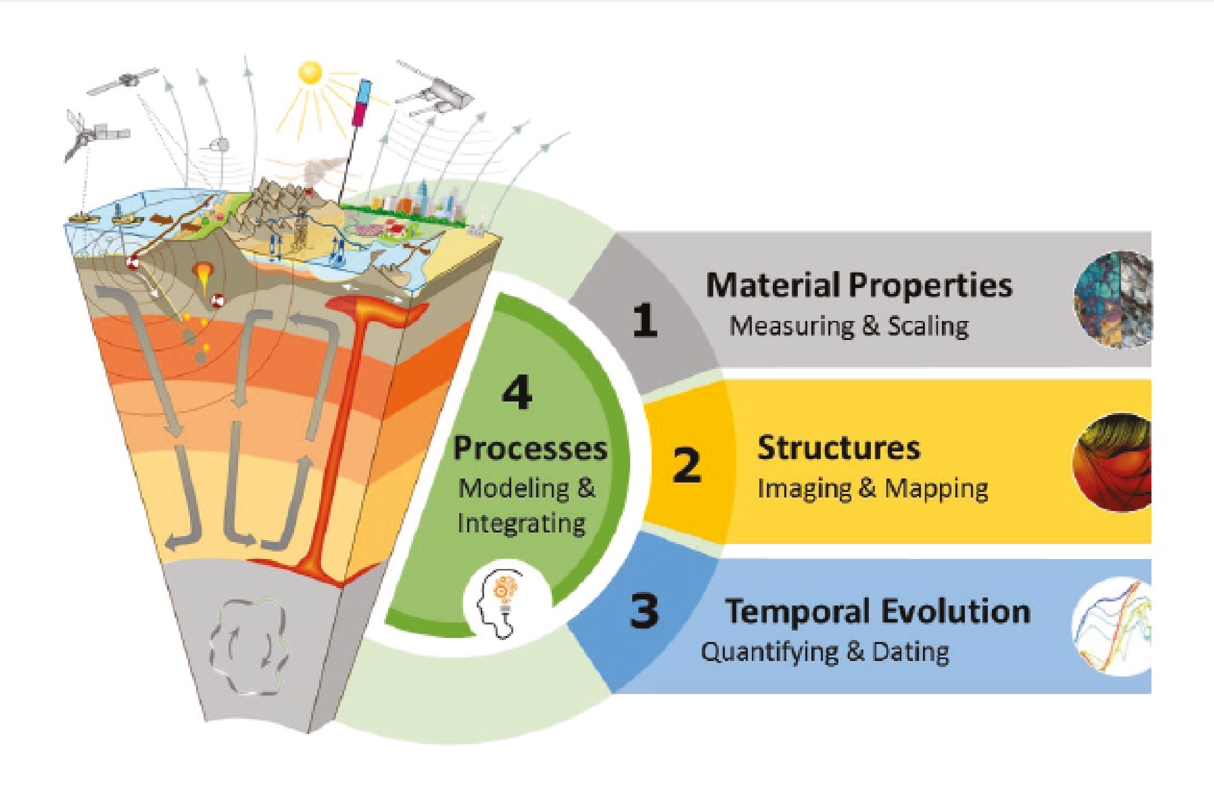

Fig. 3.4: Subtopic 3.1 will integrate laboratory-defined material properties with geological observations (structures, mapping) and age dating into 4-D models of geoprocesses that drive geohazards.

[103] *Shprits YY, et al. 2018. The dynamics of Van Allen belts revisited. Nature Physics. 14(2):102–103.

Subtopic 3.2 Temporal variations and the late stage before catastrophic events

Heidrun Kopp, GEOMAR; Patricia Martinez Garzon, GFZ

Scope and challenges. Laboratory and field observations show that the transition from the slow buildup in geodynamic loading to extreme release events occurs as a **transient process** in which the onset of deformation is accompanied by changes in material properties. These changes may occur over time scales of years, and not only minutes and hours as thought a decade ago. For example, changes have been observed that lasted several years preceding large earthquakes, such as the 2011 M 9.1 Tohoku earthquake in Japan.[104] We will address this research issue and analyze relatively short temporal variations (in terms of geological time scales) and the late-stage (years, hours, and minutes) 'preparatory phases' **when natural and human-made geological processes** develop into extreme events.

Main objectives. The focus here is on a holistic investigation of temporal variations (transient phases) using laboratory experiments, modeling, and field observations over local, regional, and global scales. This involves understanding and modeling the fundamental physical processes that control temporal variations, requiring new monitoring approaches in order to separate long-term, steady-state behavior from short-term signals, to reduce the signal-to-noise ratio of the observables, and to identify emerging threats. While the natural Earth system will be the primary focus, events associated with geothermal and gas production activities (with links to T8) may be considered as 'controlled' experiments that will help in developing our understanding.

Work program.

1. **Application of technological advances in observational methods** in geodesy (e.g., new satellite missions, expanded GNSS, seafloor geodesy), seismology (e.g., highly sensitive observatories, dense networks made up of large numbers of sensors), airborne observational systems (e.g., UAVs for repeat surveying of landslide scars and volcanoes) and analytical techniques (e.g., high-resolution geochemistry and geochronology, fiber-optic sensing). These will quantify not only drivers (cf. ST3.1) but also **temporal variations** (this Subtopic) and processes at unprecedented precision (Fig. 3.5), allowing even low-magnitude temporal changes (e.g., deformation, gas emissions) to be observed.
2. **Evaluate, focus and further extend the observational infrastructure** of monitoring networks (e.g., SMARTcable and fiber-optic sensing wet demonstrator) and PBOs, concentrating on a few key sites, and extending the laboratory capabilities. A stronger emphasis in the experimental work (e.g., rock mechanics, geochemistry, analog models) and observation focus will be placed on the detection of transient preparatory phase phenomena. We will expand **multi-parameter observations** on short-time scales in areas where transient episodes are expected or observed (e.g., subduction zones in Chile and Western Canada, Mt. Etna). The recent detection of seismicity beneath the Eifel volcanic field,[105] Germany, is also a motivation for developing a new observatory to investigate volcanic transients.
3. **Application of new signal processing and data-mining techniques** will incorporate methodological advances and contribute to the rapid identification of transients and their interactions in the Earth's crust. Such techniques will include machine and deep learning methods being applied to large datasets (e.g., the Incubator project MAP – Machine Learning based Plasma Density Model.)

[104] Mavrommatis AP, et al. 2014. A decadal-scale deformation transient prior to the 2011 Mw 9.0 Tohoku-oki earthquake. Geophysical Research Letters. 41(13):4486–4494.

[105] *Hensch M, et al. 2019. Deep low-frequency earthquakes reveal ongoing magmatic recharge beneath Laacher See Volcano (Eifel, Germany). Geophysical Journal International. 216(3):2025–2036.

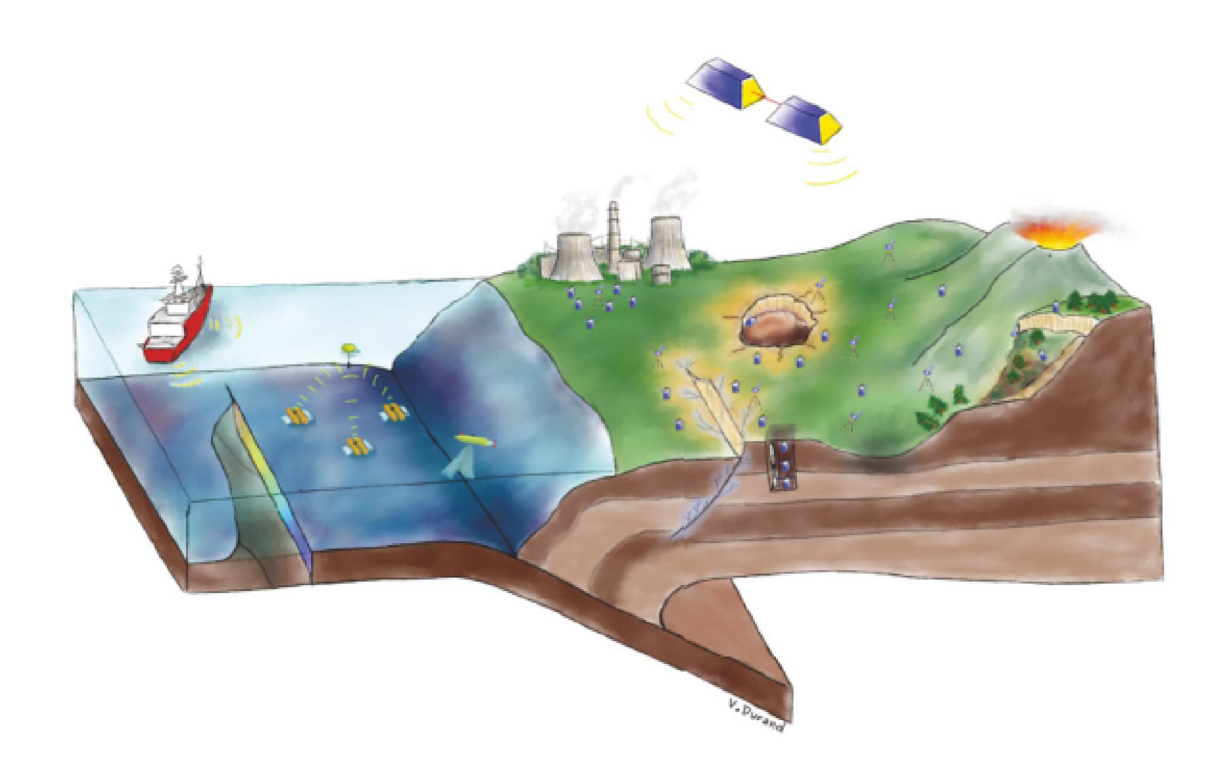

Fig. 3.5: Land-sea-space integration of observatories and networks will target geohazards related to earthquakes, volcanoes, landslides, sinkholes, and subsidence.

Deliverables (D) and Milestones (M)

- **D3.3 (2027):** Methodological framework for the detection, identification, and analysis of preparatory processes related to various hazards using state-of-the-art field monitoring. **M3.3-1 (2021):** Establishment of the next generation of PBOs, especially at the land-sea interface (e.g., Mt. Etna crossing-the-shore-line observatory), and the development of new transient observatories (e.g., an Eifel transient observatory). **M3.3-2 (2023):** Establishment of a sea, land, and space task force(s) to instrument regions experiencing transient episodes and the potential build-up to extreme hazardous events.
- **D3.4 (2027):** Development of the next generation of modeling and laboratory investigations of preparatory phases to enable the forecasting of geohazards by incorporating new constitutive relations describing material behavior. **M3.4-1 (2023):** Completion of laboratory and in situ experiments that constrain the values at which parameters relevant to different geohazards under controlled conditions fail. **M3.4-2 (2025):** Development of constitutive laws that capture the complex behaviors (e.g., non-linear deformation) that precede different geohazard events and their implementation into state-of-the-art 4D forward models.

Subtopic 3.3 Extreme events: characterization, cascades and impact

Elenora Rivalta, GFZ; Thor Hansteen, GEOMAR

Scope and challenges. The physical understanding, rapid (real-time) characterization and quantification of the potential impact of extreme events are the main concerns of this Subtopic. We will investigate three different types of extreme events (Fig. 3.6): i) **Events that affect areas of an extreme spatial extent,** such as a magnitude 9 earthquake, 'super-volcano' eruptions (volcanic explosivity index 8), mega-tsunamis, or extreme solar storms. While these events are extremely rare, they would have major and long-lasting consequences on the global economy and even civilization as a whole. The rarity of such events, however, means that there are few if any instrumentally recorded examples. Hence, there is a need to exploit the geological record of past events and to develop simulated databases to study them. ii) **Moderate magnitude events** that, if occurring today in proximity to urban areas, would inflict serious economic and societal costs (e.g., a repetition of the 1356 Basel Earthquake). Such events are relatively common globally, hence allowing more in-depth studies of the involved processes. iii) **Multi-hazard cascade events** are where interactions between processes lead to major cumulative impacts (e.g., the interaction between volcanism and landslides[106]). A recent example is the 2018 Palu earthquake (Indonesia), which caused the liquefaction of soft sediments, causing major structural damage while also triggering submarine landslides, resulting in a devastating tsunami. Such studies require the combination of sea-land-space observations, especially considering that the most devastating events in recent years have all crossed the sea-land boundary.

Main objectives. Coupled physical-chemical and mechanical models, including laboratory-, numerical- and probabilistic tools, will contribute to understanding the development of extreme events. Realistic scenarios, including uncertainties, will be developed and combined with numerical tools and web-based services for the simulation of single- and multi-hazard cascading events. The enhanced understanding, combined with data science developments, will facilitate innovative methods for event detection, simulations, and forecasting of possible 'black swan' events.

Fig. 3.6: The classification of extreme events followed in Subtopic 3.3, demonstrated for a volcano example of extreme size (magma chamber under Toba super volcano; top), with high impact (Naples city and Vesuvius; middle), and cascade events (Eyjafjallajökull ash leading to prolonged disruption of the aviation industry; bottom).

[106] *Maccaferri F, et al. 2017. The effect of giant lateral collapses on magma pathways and the location of volcanism. Nature Comm. 8(1):1097.

Work program. The work program is divided into three parts:

Forensic analysis of past events. High-quality (complete within a given time period) catalogs and geological archives of extreme events are essential for developing and validating the scenarios, and to quantify the impact of future extreme events, as well as describing their future occurrence in a probabilistic way. New forensic analysis methods will be developed to better understand cascading phenomena (focusing on massive marine landslides triggered by earthquakes, or volcanic eruptions that generate tsunamis).

High resolution and global characterization of extreme events. This may be realized at a few, well-selected sites, e.g., in seismic gaps where participating centers operate observatories. However, because of their rarity, there is a risk that no event will occur at these sites during the PoF IV period. Thus, we will monitor multiple sites simultaneously. This is possible because global observations are now accessible by open data policies organized within frameworks like the European Plate Observing System (EPOS[107]) or the European Space Agency (ESA) satellite missions of the Copernicus program.[108] Advances in data science will also lead to improvements in the capacity for data handling and the autodetection of relevant information. The new sensors and platforms (fiber-optic cables,[109] gravimeters, micro-seismometers) will allow rapid deployment from vessels-of-opportunity. Novel multi-parameter source inversion methods will be tested at the pilot sites and on global scales. Realistic multi-hazard simulations in pilot regions (e.g., Chile, Mt. Etna[110]) will be developed and used to estimate site effects, infrastructure damage and losses based on exposure and vulnerability models (link with ST3.4). Finally, crowd-sourced approaches (e.g., peaks in the access rates to websites, tweets with certain keywords) will be integrated into the data analysis framework.[111]

Modeling future extremes beyond past events. By combining physics-based simulation tools with probabilistic and data-mining approaches, new opportunities for understanding the natural process chains and tipping points that culminate in extreme events will be developed. These simulations will be integrated with vulnerability and exposure models as part of ST3.4 to estimate potential damages, losses, and fatalities, including the transparent communication of their uncertainties.

Deliverables (D) and Milestones (M)

- **D3.5 (2027):** Development and field testing of a collection system for the observables related to the occurrence of extreme events. **M3.5-1 (2024):** The development and deployment of new sensors suitable for urban environments and integrated urban fault/volcano observatories. **M3.5-2 (2024):** The development of techniques for the inversion of earthquake source parameters from gravity changes measured by the GRACE-FO mission. **M3.5-3 (2024):** Completion of the forensic analysis of historic events, focusing on massive landslides, identifying fault traces, tsunamis, and explosive volcanic eruptions. **M3.5-4 (2025):** Development of automated methods for collecting and processing in situ and satellite-based data (e.g., global volcano and seismic monitoring).
- **D3.6 (2027):** The identification of the specific factors behind extreme and high-impact events. **M3.6-1 (2023):** The development of realistic scenarios (including uncertainties) that are combined with numerical tools and web-based services for the simulation of single- and multi-hazard events. **M3.6-2 (2025):** Development of an integrated monitoring and data assimilation strategy that will reduce the uncertainties of extreme event forecasts.

[107] See https://www.epos-ip.org/.

[108] See https://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus.

[109] *Jousset P, et al. 2018. Dynamic strain determination using fibre-optic cables allows imaging of seismological and structural features. Nature Comm. 9:2509.

[110] *Urlaub M, et al. 2018. Gravitational collapse of Mount Etna's southeastern flank. Science Advances. 4(10):eaat9700.

[111] *Steed R, et al. 2019. Crowdsourcing triggers rapid, reliable earthquake locations. Science Advances. 5(4):eaau9824.

Subtopic 3.4 Translating hazard knowledge into risk mitigation

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Scope and challenges. One of the greatest challenges in protecting society from geohazards is converting the acquired knowledge about these hazards into practical means of mitigating against the most serious consequences of such events.

Main objectives. There are three objectives: i) raising community awareness and preparing decision-makers charged with long-term urban planning or site selection/design of critical facilities, ii) improving short-term (days, hours, seconds) warnings,[112] and iii) contributing to rapid response and real-time information during the hours/days following a major event.

Work program.

Awareness and long-term urban planning. The Subtopic will contribute to the next generation of tsunami, volcanic and seismic hazard maps/models tailored for enhancing public awareness and preparedness, refining zoning and building codes, and the design and siting of critical facilities. Dense observations (GNSS, seismic imagery) will support the definition of geomechanical models of major faults, allowing forecasts of the characteristics of future earthquakes and tsunamis. Low-cost sensors imbedded in buildings and the use of fiber-optic cables, developed in ST3.2, will help locate urban faults and to record earthquakes and other ground movements within cities. The new seismological records and 3D wave propagation models will improve the evaluation of future shaking scenarios by taking into account local ground conditions, particularly important for cities and critical facilities in large basins (e.g., the Rhine graben) or close to major faults (e.g., Istanbul[113]). The development and expansion of Urban Fault (and Volcano) Observatories (e.g., GONAF+) will adapt such monitoring systems to urban environments. The new generation of hazard models will be developed under the umbrella of European infrastructures (e.g., EPOS) and building codes' committees,[114] and will be embedded in probabilistic risk computations while allowing for cost/benefit analysis of mitigation actions.

Warning. The new generation of Tsunami Early Warning (TEW) systems will integrate data from modern GNSS and undersea cable networks. This integration will require developments in several directions, including real-time GNSS signal processing, local feasibility studies, and Observation System Simulation Experiments (OSSE). We will evaluate decentralized earthquake early warning/rapid response architectures[115] based on widely distributed smart sensors. Moreover, the information required to trigger a warning can be exploited to provide rapid loss estimates based on dynamic exposure modeling. We will make significant improvements to forecasting the near-Earth space weather by developing forecasting tools for the near-Earth radiation environment. This will include a new model for predicting the Kp-index, the internationally most widely used index for space weather services, as a real-time product with enhanced temporal resolution.

Rapid response and post-event information. The participating centers in T3 are setting out to become the go-to source of information on hazard events. Information material will be tailored for a wide range of users' expertise, from scientific experts to policymakers, industry, first responders, and the general public. An internal rapid data exchange platform will be developed with the goal of providing information about extreme events by exploiting data science and automatizing event-detection (e.g., GEOFON).

Deliverables (D) and Milestones (M)

- **D3.7 (2027):** Design of the next generation of early warning and rapid response systems. **M3.7-1 (2022):** Develop tools for the rapid and transparent dissemination of information about extreme events via appropriate web services. **M3.7-2 (2024):** Design a new generation of TEW systems that integrate modern GNSS and undersea fiber-optic cables and prepare it for deployment. **M3.7-3 (2025):** Design a new gen-

[112] *Lauterjung J, et al. 2014. The Earthquake and Tsunami Early Warning System for the Indian Ocean (GITEWS). In: Wenzel F, Zschau J, editors. Early Warning for Geological Disasters: Scientific Methods and Current Practice, Springer. p. 165–178.

[113] *Lange D, et al. 2019. Interseismic strain buildup on the submarine North Anatolian Fault offshore Istanbul. Nature Comm., in press.

[114] *Grünthal G, et al. 2018. The probabilistic seismic hazard assessment of Germany—version 2016, considering the range of epistemic uncertainties and aleatory variability. Bulletin of Earthquake Engineering. 16(10):4339–4395.

[115] *Parolai S, et al. 2017. Assessing Earthquake Early Warning Using Sparse Networks in Developing Countries: Case Study of the Kyrgyz Republic. Frontiers in Earth Science. 5:74.

eration of decentralized early warning systems adapted to industry and moderate seismicity areas. **M3.7-4 (2026):** Implement a new model to forecast the magnetospheric ring current, radiation belts, and the Kp-index.

- **D3.8 (2027):** Time-dependent geohazard forecasts targeted to modern urban risk assessments. **M3.8-1 (2022):** Delivery of seismic zonation and volcanic hazard maps for Germany adapted to critical facilities design and radioactive waste site selection. **M3.8-2 (2024):** Global Earthquake Model (GEM, phase 3) implemented, involving a testable, harmonized, and time-dependent seismic hazard and risk model.

E) Previous achievements of the contributing centers and infrastructure

Expertise and preliminary work. As the largest georesearch center in Europe, GFZ has developed a unique level of expertise in geohazards. A key strength is the extensive research infrastructure which includes a unique assemblage of laboratories, long-term observatories, and information services based on global networks (e.g., GEOFON), operated within the LKII infrastructure MESI and is thus open to external researchers. Furthermore, the GFZ is involved in Earth observation missions (e.g., GRACE-FO, SWARM) and coordinates the International Scientific Continental Drilling Program ICDP. GFZ has a concentration of geohazard expertise and is leading initiatives at the regional (e.g., Geo.X, Research Network for Geosciences in Berlin and Potsdam[116]), and national levels (e.g., earthquake hazard maps for building codes), and is a major contributor to actions at the European (e.g., EPOS) and global scales (e.g., GEM[117]). Future developments include advances in remote sensing technology and enhancing its capacity in data science. GFZ is a prime player in earthquake and tsunami early warning systems (e.g., German Indonesian Tsunami Early Warning System – GITEWS[118]). Furthermore, GFZ attracts international scientists and collaborative research projects. In addition, a number of spin-off companies have been created in the solid Earth and geohazards fields.[119]

GEOMAR is world-renowned for its observational and technological seagoing capabilities, which permit the investigation of the causes and nucleation processes of volcanic eruptions, earthquakes, sector collapses, submarine landslides, and tsunamis in the world's oceans and at the land-sea interface. This relies on a broad portfolio of seagoing instrumentation ranging from seafloor-based to towed instruments, autonomous and remotely operated vehicles (e.g., ROVs, AUVs, UAVs) and gliders (e.g., potential link with the agrorobotics in T7). GEOMAR has recently established a volcanological UAV group to complement offshore surveys at volcanic islands and coastal volcanoes with shallow marine and subaerial investigations. GEOMAR's ocean bottom seismometer pool is one of the largest in Europe. GEOMAR also operates the largest seafloor geodetic array worldwide (GeoSEA).

Uniqueness.

- The combination of observational infrastructure made available by the partners allows research activities that cross the **land-sea** (and space) interface (see Fig. 3.7).
- GFZ and GEOMAR will together continue to follow a **multidisciplinary** systems approach, involving the integration of field, laboratory analytical and instrumental observational competence.
- T3 sets out to bridge the **different time scales** between those at which the deep-Earth processes that cause geohazards operate (the geological time scale) and those associated with the events themselves and their aftermath (human time scale).
- The Topic's breadth of expertise allows the **full risk chain to be holistically explored.** This includes a time-dependent, multi-hazard perspective that recognizes the need for urban risk models that include infrastructure covering the land, sea, and near-space environments.

[116] See https://www.geo-x.net/en/.
[117] See https://www.globalquakemodel.org/.
[118] See https://www.gitews.org/en/homepage/.
[119] Gempa GmbH, DIGOS, Quakesaver, Dynafrax.

Infrastructure and specific resources. The participating centers operate a large range of LKI category equipment for terrestrial and marine surveys and have access to remote sensing technologies. These assets are complemented by state-of-the-art laboratories for mineralogical-chemical analysis, experimentation under controlled high p-T conditions, and dedicated sub-surface research facilities (e.g., the KTB deep observatory[120]), along with HPC numerical simulation platforms, and research infrastructure in LKII. The following activities will be of particular importance to this Topic's strategy.

- **High-density monitoring of specific targets.** The permanent PBOs in the Chilean subduction zone (IPOC) and the Marmara Sea region in Turkey (GONAF), as well as various networks in Central Asia (Global Change Observatory) and at Mt. Etna constitute key focus sites. These are, therefore, ideal for high-density monitoring for hazard research. The existing installations at these sites will be flanked by dedicated temporary networks from the GIPP in order to obtain detailed structural images and to monitor possibly active deformation processes. The **planned extension of PBOs to urban areas** (e.g., Istanbul, Bishkek, Valparaiso, southern Sicily) will allow the development of new methods for assessing urban risk and develop monitoring systems adapted to urban environments.
- **Global monitoring systems.** Hazard research is highly dependent on global monitoring using both ground-based networks and space-borne systems. MESI provides these observational systems, as well as monitoring networks like GEOFON, and various geodetic products as part of the IAG services (International Association of Geodesy). These GNSS systems will be regularly updated to provide improved accuracy, higher frequency, and real-time data processing.
- **New monitoring systems and methodologies to detect transients, material changes, and fluid movements.** Such systems will include the processing of data from fiber optics cables and high-density seismic experiments, the implementation, and analysis of seafloor geodesy, remote sensing observational platforms, and the coupled analysis of remote sensing, seismological and magnetotelluric data.
- **Transient Task Force.** A multi-parametric **rapid response group** will be established for installing temporary monitoring instrumentation at sites where preparatory phase phenomena (e.g., earthquake swarms, deformation transients, thermal transients, volcano unrest) have been detected or where climate change may trigger such. This concept is a development on the existing task force at GFZ, which is deployed in response to the occurrence of large events, and on the UAV groups at both GFZ and GEOMAR that jointly monitor activity of geohazards.

F) Collaboration and transfer

Management and organization.

- The centers involved will formulate yearly implementation plans of the T3 research and recruitment strategy to further develop the centers' key competences (as recommended in the PoF III evaluation). Plans will include the integration of relevant third-party funded projects (e.g., ERC) and detail the establishment, expansion, and exploitation of observatories under their control.
- Large investments and key partnerships (e.g., Helmholtz strategic investments, marine campaigns) will be organized at the Topic level (e.g., ongoing discussions for turning intercontinental communications cables into environmental sensors).
- Internal thematic workshops (with international partners) are planned in order to inspire new ideas, ensure a bottom-up approach, and to integrate early career scientists.[121]
- A joined mobility program (internal sabbatical mobility and joint invitations of high-level international guests) will be organized to stimulate networking, generate new ideas, and integrate the prominent scientists into the Topic's program.

[120] See https://www.gfz-potsdam.de/en/section/geomechanics-and-rheology/infrastructure/ktb-deep-crustal-lab/.

[121] Two workshops ('Transients on faults', Potsdam 4th and 5th April 2019, 'Linking Deep Earth to Surface: Geohazards, Geodynamics, Geomaterials', 25th March 2019) have already been held.

Partners. The partnership will follow a dedicated strategy (Table 3.1): i). To address the global scale of the challenges outlined above, we will collaborate with **other global Solid Earth research players.** ii) The development of uniquely large and diverse databases will dictate our strategy to integrate into our training activities the **next generation of computer geoscientists** by collaboration with academia. iii) The partners will build upon and expand innovative **transfer activities** based on existing involvement with private-public partnerships (e.g., GEM), building codes standards committees (e.g., DIN), and civil protection agencies. iv) **Outreach, training, and education** in geohazard related issues will be strengthened. Such actions will increase the awareness of the relevant issues across a broad spectrum of the community.

Positioning of the Topic in international research. T3's research will contribute to all priority areas of the Sendai Framework: i) understanding disaster risk, ii) strengthening governance to manage disaster risk, iii) Investing in disaster risk reduction for resilience, and iv) enhancing disaster preparedness for effective response. T3's involvement with other international initiatives include GEM, GTM (Global Tsunami Model[122]), IN-MHEWS (International Network for Multi-Hazard Early Warning System[123]), ICG/IOTWMS (Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System[124]) and ICG/NEAMTWS (Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas[125]).

Considering the range of methods and expertise covered, the Topic partners are well-positioned for leadership within the geohazard and risk research communities. Several aspects of the Subtopics (transients and 'preparatory phases', new urban risk assessments, novel sensors, as well as the focus on extreme, high-

Table 3.1: Summary of general recommendations (repeatedly) addressed in the six PoF III evaluation reports.

	Keys partners	Joint efforts
Academic partnership (National)	German academic consortium at the interface between data-science and geosciences (e.g., Geo.X and MARdata)	New methods related to data mining and digitization. Training (undergraduate and graduate students, focus on big data)
Academic partnership (International)	ICDP, IODP, EPOS (EU-infrastructure), international collaborations associated with PBOs (Chile, Turkey, Cascadia, Central Asia) and volcano observatories (Etna, Italy and the Eifel, Germany)	Development of plate boundary and urban fault observatories Global monitoring of geohazards International data management strategies
Transfer (Public Sector)	Disaster and Emergency Management Authority in Turkey; Ministry of Emergency Situations, Kyrgyz Republic; Federal office of Civil Protection and Disaster Assistance, Germany; DIN	International training courses (focus on emerging disciplinary fields and methods) Operational mitigation and early warning. Community awareness. Knowledge exchange
Transfer (Private Sector)	Public-Private partnership (GEM); Spinoffs (e.g., Gempa); International companies (Deutsche Rűck, EDF)	Safeguarding facilities and lifelines. Stakeholder awareness and training. Job creation

122 See https://edanya.uma.es/gtm/.
123 See http://www.wmo.int/pages/prog/drr/documents/IN-MHEWS/IN-MHEWS.html.
124 See http://www.iocperth.org/iotwms.
125 See http://www.ioc-tsunami.org/index.php?option=com_content&view=article&id=10&Itemid=14.

impact events) are at the forefront of research and will employ cutting-edge approaches. Furthermore, with our work on data interoperability and rapid, easy availability, we aim to create a major global asset available to all researchers and stakeholders.

Opportunities and Risks. The primary and potentially most beneficial opportunities in PoF IV will arise as the result of **enhanced collaboration between the centers.** Such opportunities include the combined **land-sea** observations at the PBOs, the rapid response to large events, as well as the joint interpretation and coordinated dissemination of results. Furthermore, the partners will jointly develop advanced monitoring technologies and modeling tools. The combined strength of the two institutions will make them extremely-well positioned for **global leadership** and collaboration with other major institutions, such as the BGS UK, ETHZ Switzerland, USGS USA, ERI and NEID Japan, INGV Italy, and EOS Singapore.

One concern that may hinder some ongoing activities is related to political situations. For example, GEOMAR has been prohibited from retrieving scientific instruments from the Marmara Sea, despite close collaboration with its Turkish partners. Much of the marine work is dependent upon future ship-time availability, and there are risks involving this. Coupled with these issues is the potential that deployed instruments are damaged, sometimes as a result of the geohazard events they are meant to monitor. It is also essential to take advantage of new technological developments by replacing outdated analytical infrastructure with state-of-the-art instruments.

From a scientific perspective, there is no guarantee that the preparatory phase of an event will be identified in a systematic way. However, this risk is greatly outweighed by the potential gains. If these activities are successful, it will lead to a **paradigm change** with significant impacts on the use of early warning systems and time-dependent hazard assessment.

Cross-Topic and Cross-Program-Activities. One of the main Cross-Cutting Activities (CCA) involving T3 deals with **urban spaces.** This requires a risk framework linking T3 with T4 (coastal zones) and T5 (floods), as well as assessing the impact of various hazard types on the urban environment. Together with T1, T2, T5, and T6, T3 will also develop a concept addressing **extreme events** in a changing world from a multi-hazard perspective. This will involve exploring how independent events may occur within close temporal and spatial proximity (compound hazard), and how a given event may trigger subsequent (cascade) events, e.g., torrential rain triggering landslides. In addition, the geodynamic research in T3 is strongly linked to activities in T8 in terms of understanding resource formation and the hazards associated with some forms of energy production. This will include contributions to two CARFs with RF Energy: **'Geoenergy'** and **'Nuclear Repository Research'**. T3's experimental research will also form part of the collaborations with DESY, focusing on the RF Matter, within the framework of the interdisciplinary 'Center for Molecular Water Science'. Finally, exploiting the latest advances in **data science** and **exascale modeling** will see collaboration with programs such as Digital Earth and ESM (Earth System Modeling[126]).

Transfer and contribution to SynCom. T3's contribution is summarized as follows:

- The rapid provision of relevant and targeted post-event information (e.g., to the media) describing an event, including potential losses, and the dissemination of long-term educational awareness material about geohazards and multi-hazard processes. Furthermore, in the aftermath of major events, the scenarios developed as part of this Topic will be used to communicate the possibility and consequences of such events in Germany or close to the world's mega-cities.
- The inclusion of new risks not yet identified, or insufficiently recognized. Examples include space weather and its impact on powered infrastructure, marine slope instability due to gas hydrate dissociation, and induced seismicity from geothermal exploitation.[127]
- The Topic will emphasize the relevance of the long-term or geological perspective, considering analogies with past geological events, and the impact of the changing climate on some geohazards, such as landslides.

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[126] See https://www.gfz-potsdam.de/en/section/earth-system-modelling/overview/.

[127] *Grigoli F, et al. 2018. The November 2017 Mw 5.5 Pohang earthquake: A possible case of induced seismicity in South Korea. Science. 360(6392):1003–1006.

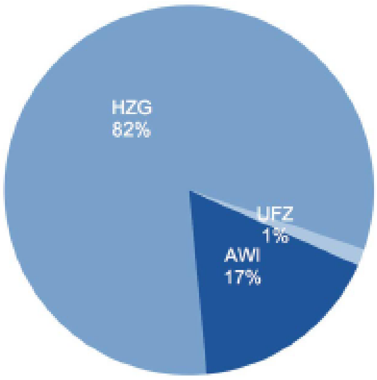
- T3's research will result in a unique series of sea-land-space integrated datasets. Such datasets, at the international level, will contribute to the exploration of profound scientific questions (planetary temporal evolution, preparation phases of catastrophic events, post-event recovery phase of earth materials) by the broader scientific community. This will necessitate the close interactions between laboratory, numerical, and field activities.

Executive Summary

- T3 will provide a holistic framework for understanding and forecasting geohazard events by employing unique sea-land-space observation frameworks and innovative developments in modeling and data science, with a special concern for urban environments. T3 will investigate the multi-scale coupling of Solid Earth system processes and address fundamental scientific questions (e.g., the preparatory phases of extreme events, dynamic interactions surrounding cascade processes). The Topic's outcomes will address new geohazard threats due to climate change, urbanization, and the use of the near space. Taking advantage of new technologies, T3 will provide the rapid, transparent, and reliable information expected by the scientific community, decision-makers, and the general public.
- T3 will primarily contribute to the Program objectives 4 (understanding the drivers of geohazards), 5 (mitigating against urban risks), 8 (development of sustainable options for natural resources), and 10 (ensuring the sustainable future of humankind).
- T3's major contribution to the Program as a whole will be to unite and strengthen the efforts of the relevant Helmholtz centers. This is in order to provide cross-disciplinary methodologies and tools for monitoring, assessing, and communicating knowledge of the drivers and consequences of geohazards, from frequent lower impact events to those with potentially global reach.

Topic 4: Coastal Transition Zones under Natural and Human Pressure

Spokespersons: Daniela Jacob, HZG; Karen H. Wiltshire, AWI



Topic 4 develops multi-use scenarios for sustainable coastal systems with climate change to enhance our understanding and to support science-based decision-making. Considering international frameworks and agreements such as the SDGs, the Sendai Framework and the Paris Agreement, Topic 4 research focuses on the process understanding of energy and matter fluxes across compartments, their impacts on ecosystems functioning and ultimately on human societies. The ambitious integrated systems approach includes single and multiple stressors or drivers, considering the influence of human activities and climate change. New scientific evidence will contribute to identifying trade-offs in the system, informing decision-makers and will support the development of new and enhanced governance structures.

A) Scope and challenge of the Topic

Research subject. In this Topic, coastal systems are defined as the contiguous space of the 'dry' coast, estuaries, rivers and hinterland, and coastal ocean and shelf sea. They are also rapidly and, in some cases, catastrophically changing – forced by climatic, environmental and socio-economic drivers. There is an urgency to limit climate change and to adapt to future states of the coasts (Paris Agreement), reduce the risk for human communities and their coast-dependent livelihoods (Sendai Framework), and to plan for a future and sustainable state of the coasts characterized by increasing and accelerated urbanization (SDGs). Furthermore, the EU's 'Blue Growth' strategy and other sectorial ambitions require the sustainable development of coastal systems with its high potential for sustaining jobs and economic development. Linking international policy to local action is critical to achieving healthy coastal systems in the future.[128]

Topic 4 (T4) will initiate and further develop platforms and methods for integrated observation, predictive modeling tools, and novel system-analysis. T4 establishes science-based information streams and packages for different plausible and desirable future states of coastal systems. These will support specific management decisions and coastal system governance. The analysis is not limited to single stressors and drivers but uses novel approaches to address the entire system dynamics and integrate the effects and feedback of human needs and activities as part of the coastal system. It studies the continuum of climate – environment – organism – eco-

[128] *Glavovic BC, Limburg K, Liu KK, Emeis KC, Thomas H, Kremer H, Avril B, Zhang Z, Mulholland MR, Glaser M, Swaney DP. 2015. Living on the Margin in the Anthropocene: engagement arenas for sustainability research and action at the ocean-land interface. Curr Opin Environ Sustain.14:232-238.

system to the entire coastal habitat, including anthropogenic impacts and societal needs across spatial scales, while considering the past, present, and future.

The development of pathways towards the desired futures is intended to inform multi-level decision- and policymaking in the public and private sectors. It will consider common and global policy benchmarks, e.g., the IPCC scenarios for a 1.5°C or 2°C warmer world. This Topic creates the research framework within which the potential risk resulting from actions along the pathways, including consequences for marine resource utilization, offshore energy production, marine aquaculture, and water quality will be considered.

Explanation and justification of research. Coastal and shelf seas are fundamentally important for the sustainability and enhancement of human welfare and industry. It is forecasted that between 50 and 70% of the population will be living in coastal areas[129] in the next 50–100 years, which creates competing demands from different sectors on scarce coastal and shelf sea resources. Examples are: coastal fisheries and marine aquaculture as a main source of protein for three billion people; tourism – the fastest growing global industry – which heavily depends on healthy coastal systems, pristine environments and maritime infrastructure; biodiversity of species and habitats, which provides essential ecosystem services such as carbon sequestration and uptake, and contributes to human recreation. Coastal systems are also an important resource for renewable energies and marine mining. Notably, the high biodiversity and unique ecosystems of coastal systems require study and protection.

To address these competing demands in the light of global and climate change, and in order to contribute to the development of management solutions, a **systems approach** is applied in T4. Our research activities will significantly enhance the understanding of the coastal transition zone as a system and will identify which processes society **can influence or even govern** in coastal zones. This provides the basis for climate change mitigation and risk reduction. It also allows the identification of those consequences of global and climate change that either **cannot, or are unlikely to, be mitigated.** This provides guidance on where and how society must adapt.

Strategic guidelines (FoPoZ). T4 works towards strengthening the management of sustainable and resilient coastal transition zones including urban spaces, shelf and coastal seas as well as small islands in a warmer climate and under global and regional change. It underpins effective management with research leading to sustainable and habitable coasts by 2050 and explicitly transfers concepts and methods to societal and institutional stakeholders. For this purpose, T4 will push the development and integration of observations and data infrastructures (such as COSYNA, MOSES, DANUBIUS-RI with HCDC and NFDI) accessible for scientific and societal users (e.g., DAM, BSH, NWKLN). Research products expected from T4 include a coastal pollution toolbox in Subtopic 4.1 (ST4.1), extended coastDat regional climate reconstructions in Subtopic 4.2 (ST4.2), and new climate service prototype products developed jointly through interaction with societal stakeholders in Subtopic 4.3 (ST4.3). Consequently, T4 objectives are highly aligned with those of MARE:N, for example, matter fluxes from catchment to sea, changed response times triggered by anthropogenic inputs, and integrated solutions for coastal use conflicts. T4 will (co-)develop and transfer information and services that will support solutions aimed at strengthening the resilience of coastal systems, including activities in SynCom, REKLIM and internationally in the IPBES and IPCC context. In this respect, strong connections exist and will be further developed to support science, education, and services in international networks such as POGO, IOC, SASSCAL and WASCAL in Africa and other developing Nations. Together with T6, T4 will tackle biodiversity research linking to the new BMBF flagship initiative 'Conservation of Biodiversity', with a focus on recording and assessing the extent, causes, consequences and interactions of changes of biological diversity and their protection in the transitional area between land and sea.

Function and contribution of the Topic within the Program. Integrating different modeling activities and observations with a specific focus on coupling Earth system compartments, including abiotic and biotic components of the coastal ecosystem, contributes to the overall Helmholtz competence and capacity in Earth system research. To achieve its ambitious goals, T4 takes on a specific coastal perspective and collaborates closely with T1, T2, T5, T6, T7 and T9. It is engaged in CARFs and CTAs and contributes to several scientific Program objectives to foster the Program's Earth system approach through its expertise in coastal systems.

High-resolution atmospheric modeling of local climate changes will be jointly developed with T1. A collaboration with T2 bundles sea level research and ocean warming. Together with T2 and T6, the importance of ocean

[129] UNEP 2016. UNEP Frontiers 2016 Report: Emerging Issues of Environmental Concern. United Nations Environment Programme, Nairobi.

eddies, scale interactions and shelf-ocean coupling will be addressed and the cycling and budgets of carbon, nutrients, and pollutants in the coastal and marine realms will be linked. T4 and T6 will collaborate in the area of environmental stress and its effects on genes, organisms, and communities, using different but complementary approaches to the subject. T4 and T5 will adopt a joint perspective on nutrient and pollution loads from the source to the sea, including the consequences for coastal environments under conditions of climate change. In addition, a toolkit to study land management options will be developed with T5. T4 and T7 will jointly explore coastal bio-economy potentials under global and climate change. Collaborative activities between T4 and T9 focus on complementary research on pollutants and their multi-stressor effects.

Highlights. T4 responds to acute and future challenges which coastal transition zones face under natural and human pressures.

Development of multi-use scenarios based on a systems approach. Coastal zones are investigated as a holistic system with regeneration potential that connects land-sea-atmosphere and people. The analyses go beyond single Earth system compartments and sectors. This is necessary **to identify feedbacks and synergies between natural and human subsystems and to develop multi-use scenarios for future coastal zone functioning**. For example, T4 has the capacity to identify the needs for mitigation of the effects of sea level rise on coastal areas and especially on the Wadden Sea and its ecosystem services and human usage.

These multi-use scenarios require a fundamental understanding of processes on all levels of the coastal system and cross-scale effects. Consequently, the characterization of small-scale to regional processes and quantification of fluxes across atmosphere, land, coast, and ocean interfaces are key. They will be based on integrating the outstanding observational capabilities with long-term observational datasets and preeminent modeling competencies. This allows for an **assessment of past and the prediction of future (regional climate) change and its impacts on coastal ecosystems, from genes to communities.** It comprises single drivers and the analyses of the cumulative impacts of multiple drivers and compound events. It will guide the prediction of future changes and risks, and the identification of tipping points. One regional focus will be on how the shifts in hydrography and biodiversity in the North Sea are related to climate change and whether there are tipping points in the function of the relevant food webs and their human usage.

Innovative solutions towards future resilient social-ecological coastal systems and human livelihood are based on sound scientific evidence on coastal zone functioning and consequences of, and for, societal use. T4 integrates a full suite of modeling and observation capabilities as a basis for localized, pertinent, and actionable information to inform governance and management. This approach bridges the science-society gap and supports the local implementation of global frameworks. A strong transdisciplinary process in coastal living labs facilitates the science-society interaction.

B) Main research and structural objectives

Research Objectives.

- **Objective 1:** Elaborate energy and matter fluxes (including pollutants) from land to sea and along climate gradients.
- **Objective 2:** Learn from the past to understand and predict the future: regional climate change and its contribution to coastal system changes.
- **Objective 3:** Assess the effects of single and multiple natural and anthropogenic drivers on coastal ecosystems, including invasive species and bioeconomic use.
- **Objective 4:** Develop a suite of tools, products, and methodologies to assess human impacts and impacts on humans.
- **Objective 5:** Develop an integrated/coupled modeling system, including physical-, biogeochemical-, biological-, impact- and socio-economic components.

- **Objective 6:** Establish scenarios for sustainable development of coastal systems considering climatic and non-climatic changes and assess their implications, including a focus on the increasing urbanization of coastal regions and their ecosystems (e.g., to adapt coastal cities to global warming of 1.5°C, 2°C or 3°C).

Structural Objectives.

- **Objective 7:** Develop cumulative social-ecological impact assessments for multi-use concepts to support the sustainable use of coastal spaces.
- **Objective 8:** Connect science to society through transdisciplinary and communication approaches such as innovative stakeholder dialogues and support societal transformation using climate services as a blueprint.
- **Objective 9:** Develop a modular coastal management toolkit, including the pollution toolbox, integrated modeling, data infrastructures, and governance concepts.
- **Objective 10:** Develop a strategy towards the establishment of a virtual Center of Excellence for Climate and Coastal Services.

C) Structure of the Topic and motivation of Subtopics

Introduction of Subtopics. T4 is organized in three interconnected Subtopics. In **ST4.1**, we link coastal systems to river catchments, atmospheric and ocean dynamics, particularly focusing on the transport, turnover, input, and exchange of energy and matter. **ST4.2** builds the knowledge base on variability and change of multiple natural and anthropogenic drivers and their impact on coastal ecosystems. **ST4.3** advances the relationship between social and natural sciences necessary to enable multiscale transformative governance, innovative management strategies, climate adaptation, and sustainable use of ocean and coastal resources. The Subtopics are aligned along the logical progression of understanding the physical/biogeochemical processes and ecosystems, via the influence of climate change and human activities on their trajectories, to the actions required to achieve societal transformation towards sustainability. All Subtopics contribute to the modular coastal management toolkit.

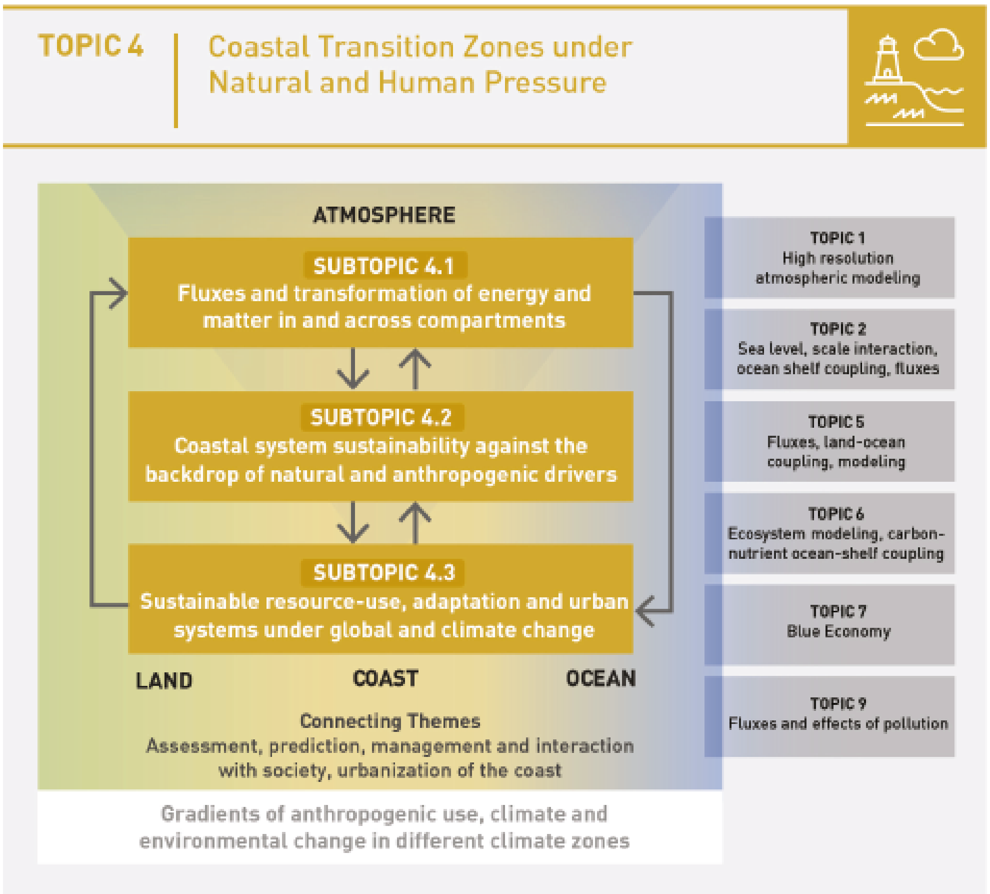


Fig. 4.1: 1 Graphical scheme of Topic 4: a systems approach.

Coastal systems are studied in Europe, the Arctic, the Southern Ocean, Asia, Latin America, and Africa (including the entire SASSCAL and WASCAL regions) and include a number of small islands worldwide. A special focus is placed on the North Sea, due to its prominence in terms of human and stakeholder needs, the large fundament of knowledge, the existent international networks and collaborations and exceptional long-term time series data including biodiversity assessments.

Contributions of the Centers to the Topic. Three centers dedicate personnel and resources to T4 (**HZG**, **AWI**, and **UFZ**), with HZG and AWI as the main contributing centers. GEOMAR is a partner regarding thematically relevant ocean interfaces of coastal systems, but with no committed resources in T4. The Institute of Coastal Research (HZG/IfK) expertise includes coastal dynamics and matter fluxes across and within coastal compartments, coupled coastal system, modeling and design and operation of state-of-the-art high-resolution coastal observations. It perfectly complements AWI expertise in coastal systems ranging from the environment to the organism and its genes, including a focus on invasive species, a key problem in warming and urbanized coastal seas. An important new building block is the UFZ expertise related to the mobilization, transport, and transformation processes of matter in the catchment-specific functional zones of inland waters. AWI will lead the multidisciplinary approaches to elucidate change effects in polar seas that are complemented by HZG/IfK expertise into joint work in high latitudes. HZG/GERICS will develop new prototype climate service products and integrated concepts with partners. It leads the strategy development towards a joint virtual Center of Excellence for Climate and Coastal Services (based on existing infrastructures) and integrates modeling of the bio-geo-physical system with modeling of human behavior. HZG/GERICS successfully applied the core concept of 'co-design and co-creation' to climate services and will further pioneer the interaction between researchers and societal actors based on the evaluation of transdisciplinary processes. AWI and HZG/IfK bring in expertise in generating knowledge from long-term observations and model-based hindcasts to future scenarios. UFZ supports these activities with their research expertise in socio-economic and governance analysis.

D) Subtopics

Subtopic 4.1 Fluxes and transformation of energy and matter in and across compartments

Kay Emeis, HZG; Sabine Kasten, AWI

Scope and challenges. The coastal zone links ocean, atmosphere, and land, and registers change in all of these three Earth system compartments. ST4.1 will differentiate the effects of **climate change** and **human regimes** in regional land-sea-atmosphere transition systems characteristic of significant ongoing or expected climatic and anthropogenic pressures. Research here focuses on the sources, transport, turnover, input, and exchange of energy and matter, both natural and anthropogenic in origin and mediation. Knowledge from long-term data and previous research will form the fundament for the evaluation of the effects of future change. System-based analyses will be conducted and will result in a consistent assessment of the multi-decadal trajectories of degradation and recovery regimes for entire catchments from the source to the sea. The outcomes will provide the scientific basis for tailored mitigation and adaptation options, specifically with respect to the role of coastal seas for carbon and nutrient fluxes, pollution, ocean health, as well as energy fluxes.

Main objectives of the Subtopic are to understand coastal system dynamics in order to unravel and attribute change to climatic and human pressures in pivotal regions across different latitudes and to identify manageable and non-manageable drivers. The Arctic and Southern coastal ocean will be focus regions primarily susceptible to global and regional climatic pressures, while European and Asian shelf seas will be cases for combined climatic[130,131] and non-climatic[132] pressures (Fig. 4.2). The three central objectives are:

[130] GISTEMP Team. 2019. GISS Surface Temperature Analysis (GISTEMP). NASA Goddard Institute for Space Studies. Dataset accessed 2019-05-27 at https://data.giss.nasa.gov/gistemp/maps.

[131] Lenssen N, Schmidt G, Hansen J, Menne M, Persin A, Ruedy R, Zyss D. 2019. Improvements in the GISTEMP uncertainty model. J. Geophys. Res. Atmos. 124:1–20.

[132] Halpern B, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, et al. 2008. A Global Map of Human Impact on Marine Ecosystems. Science. 319:948–952.

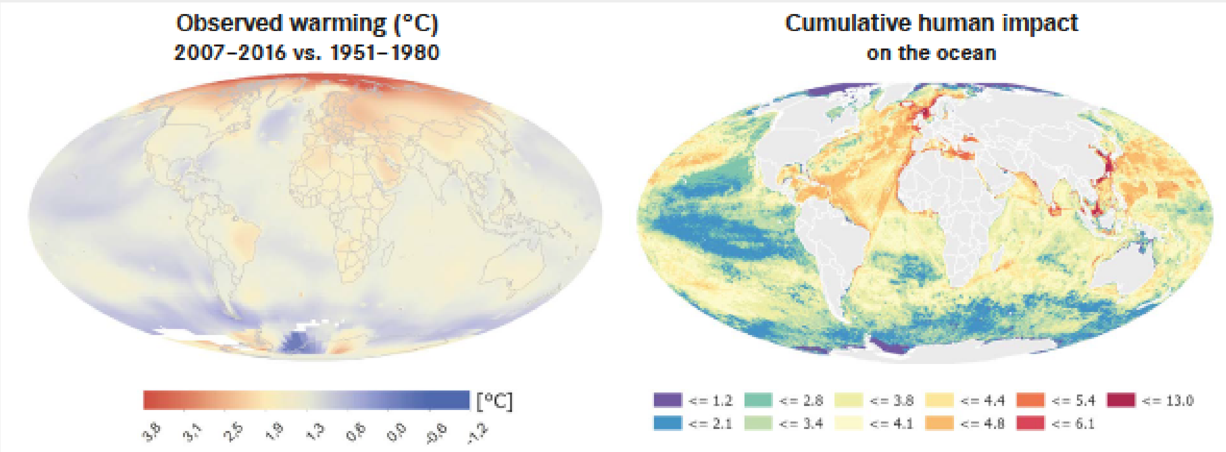


Fig. 4.2: Polar climate change[130,131] and cumulative human impact[132] on the ocean are the two dominant, spatially-disparate drivers of energy and matter fluxes in coastal zones | graphic: HZG/Ulrike Kleeberg.

- Quantify the **coastal ocean's contribution to global carbon, nutrient and trace element budgets** in response to regional climate change, human activities in the catchments and coastal zone, and interaction with the adjacent ocean. Increase and enhance synoptic regional Earth observation and modeling capacity to track change.
- Identify **pollution** origin, transport paths, and dispersal from source to sink, and evaluate the effects of complex exposition to pollutant mixtures on organisms and ecosystems. Develop an adaptive **coastal pollution toolbox** for pollution management.
- Understand and quantify fundamental turbulent and **sub-mesoscale processes** and their links to **bio-geochemical and biological responses.**[133] Particular focus is devoted to mixing and energy exchange across sub-mesoscale fronts, narrow straits and the sea surface at different wind speeds, as well as their connection to primary productivity and the distribution of organisms.

Work program. Fieldwork and modeling towards the first two objectives will focus on identifying the main **sources of nutrients, carbon, trace elements, and pollutants** at seasonal to annual time scales for selected catchment-to-ocean continua, such as the transport of nutrients from the Elbe catchment into the estuary, German Bight, Wadden Sea and North Sea (link to T2 and T6). The **transport and reaction pathways** and **fluxes between land, coastal sea, and atmosphere** will be quantified. A key deliverable will be to develop a **transient coupled benthic-pelagic module to be incorporated in state-of-the-art regional Earth system models** to assess and quantify (bio)geochemical processes and element fluxes within and across the coastal benthic and pelagic and sediment compartments and to reveal their ecosystem feedbacks. In focus are coastal sediments that are crucial sites for regulating greenhouse gases by acting as sinks, sources, or reactors for carbon, nutrients and trace elements. They include permeable sands that cover more than 50% of the shelf area and are key reaction sites mitigating anthropogenic carbon and nitrogen inputs.[134] They are also depo-centers of fine-grained sediments and thus hotspots of past and present carbon burial and exhumation. We will assess whether this ancient organic matter is susceptible to biogeochemical processing and establish budgets of carbon burial and greenhouse gas (CO_2, CH_4) release from near-shore sediments. Polar coasts are prime sources of nutrients, in particular, iron, to the adjacent ocean and drivers of the biological carbon pump.[135] The specific transport and reaction pathways of macro- and micronutrients – and specifically their response to ongoing warming – are not well constrained. We will, therefore, develop and establish innovative sampling and analytical techniques and facilities. These include trace-metal clean sampling equipment for work in harsh polar environments, non-traditional isotope systems (e.g., Fe, B), multidisciplinary lab experiments

[133] Lévy M, Franks PJS, Smith KS. 2018. The role of sub-mesoscale currents in structuring marine ecosystems. Nat Commun. 9(4758):1–16.
[134] *Ahmerkamp S, Winter C, Krämer K, de Beer D, Janssen F, Friedrich J, Kuypers MMM, Holtappels M. 2017. Regulation of benthic oxygen fluxes in permeable sediments of the coastal ocean. Limnol. Oceanogr. 62:1935–1954.
[135] Boyd PW, Ellwood MJ. 2010. The biogeochemical cycle of iron in the ocean. Nat Geosci. 3:675–682.

to explore novel biogeochemical pathways and radiocarbon dating of methane and co-occurring carbon compounds. Data sets obtained in the framework of COSYNA, DANUBIUS-RI, JERICO, MOSES, NUNATARYUK, Long-Term Ecological Research observatories[136] and ocean color satellite time series will be analyzed to assess the coupled effects of climate change, extreme events, and human-made changes in hydro-morphology and eutrophication, and to investigate the functioning of river-estuary-shelf systems in temperate land-sea transition zones. To quantify and attribute those changes on various temporal and spatial scales, smart observation techniques, such as **automated data comparison** between sensor-systems and central databases will be advanced. Automated underwater vehicles (AUVs) will be developed using real-time data of relevant processes as a trigger for deployment.

Fig. 4.3: Coastal zones receive complex mixtures of man-made substances that integrate catchment-specific human activities (industrial, agricultural, medical) | graphic: Graphic: HZG/Glynn Gorick, Icons: HZG/Maren Wilfert.

[136] E.g., LTER-D, https://www.ufz.de/lter-d/.

The **coastal pollution toolbox** transfers concepts of CARF MACE to coastal environments and ecosystems exposed to highly complex chemical mixtures originating from a large variety of point and diffuse sources (Fig. 4.3). First, it will be developed for the North Sea, where continental sources, emissions, river and atmospheric transports, and the chemical status of the coastal environment are reasonably well known. The collaboration with T9 and MACE tracks pollution (known and suspected, including plastic littering) from terrestrial to marine compartments by jointly prioritizing substance classes and empirically identifying mixtures characteristic for individual catchments and their regional atmosphere. Emission sources and source estimates will be implemented as a digital atlas/WebGIS product, along with data on target substance concentrations in different coastal zone compartments (water, sediment, biota). This digital atlas (catalog and inventory) serves as a basis for identifying coastal pollution origin and status description, in particular with respect to (as yet) non-regulated emerging contaminants. A spatially explicit **multi-compartment modeling system** for prioritized pollutants will be designed to predict their cycling between land, water, ice, and atmosphere, to verify and extend limited observations, and to keep track of changes in substance diversification. It entails an 'in-silico' evaluation of novel chemical entities (in cooperation with partners in ST9.3) for their putative impacts on organisms.

After a proof of concept phase in the North Sea, the coastal pollution toolbox will be adapted to coastal environments and catchments in **Europe**, **China**, and in the **Arctic**. The focus is initially on inventorying pollution in catchments, ice, and biota, parallel to the development of databases and models. The toolbox approach explicitly acknowledges various intensities and types of pollution, processes of emissions, transport, and interactions with ecosystems, including the accelerating release of legacy pollutants from melting or thawing Arctic ice and permafrost. The expected outcome shall give guidance for regulation, monitoring, and assessments of pollution status. It is a step towards a compact to global pollution,[137] supports regulatory bodies with information on the environmental stress and risks created by (new) pollutants, and charts most effective measures to their reduction.

The **exchange of energy between ocean eddies, fronts, and turbulence** with large-scale currents and their influence on biological production and carbon export will be investigated with an integrated high-resolution observational and modeling approach. For this purpose, next-generation instrumentation (e.g., towed-instrument array, intelligent swarm of AUVs, airborne cameras) will be developed, allowing for real-time data transmission and measurements in multiple depths and locations simultaneously. The observations will be merged with hydrostatic and non-hydrostatic models resolving the interaction of small-scale physical processes and their biogeochemical and biological responses. It is the goal to develop parameterizations for large-scale physical and biogeochemical ocean models. Of particular interest is the influence of (sub)mesoscale fronts as the associated strong motions govern (phyto)plankton and larval distribution/patchiness, growth, community structure, and population connectivity. The associated convergence and downwelling will be investigated with respect to accumulation and export of organisms and carbon (collaboration with COSYNA, T6) as well as the dispersal of floating debris (e.g., plastic) relevant for marine pollution. Vertical turbulent fluxes in shelf seas during storms will be quantified to improve estimates of heat and nutrient budgets and to assess the resilience of coastal ecosystems to climate-related changes in storm behavior. In order to better understand ocean surface waves and associated turbulent processes as a gateway for energy, momentum, and mass exchange between atmosphere and ocean, novel measurement techniques (radar, particle imaging velocimetry) are developed to capture coupled wind-wave turbulent dynamics on scales of millimeters to meters. They will be combined with heat and mass (CO_2, H_2O) flux measurements to improve model parameterizations.

Deliverables (D) and Milestones (M)

- **D4.1 (2027)**: Coupled shelf-ocean models to estimate matter fluxes and the contribution of the coastal ocean to global carbon, nutrient, and iron budgets available. **M4.1-1 (2024)**: Major processes and environmental conditions that control carbon, nutrient, and iron turnover in, and flux from, different coastal sedimentary habitats/lithologies identified. **M4.1-2 (2025)**: Regional land-sea carbon, nutrient, and iron fluxes and budgets in coastal settings spanning gradients in climate change impacts and human footprint for Arctic, Southern Ocean, European shelf seas are assessed. **M4.1-3 (2026)**: Transient benthic-ocean

[137] United Nations Environment Programme. 2017. Towards a Pollution-Free Planet Background Report. United Nations Environment Programme, Nairobi, Kenya.

model established and coupled to regional ESMs quantifying the coastal contribution to the global carbon, nutrient, and iron budgets.

- **D4.2 (2027)**: Coastal pollution toolbox available to assess origin, concentrations, and effects in coastal zones of prioritized pollutants and emergent substances. **M4.2-1 (2023)**: Substance and catchment specific prioritization scheme for regional systems spanning gradients in climate change impacts and human footprint developed. **M4.2-2 (2025)**: Digital atlas/WebGIS product on targeted substances emissions and sources, transport pathways and concentrations in compartments (water, sediment, biota) in regional coastal zones coupled to a multi-compartment modeling system for prioritized pollutants. **M4.2-3 (2026)**: Regionally specific environmental risk assessments and strategies for monitoring and management of adverse effects, developed with the coastal pollution toolbox.
- **D4.3 (2027)**: Parameterization scheme for small-scale physical processes to quantify regional impacts and biogeochemical and biological responses developed. **M4.3-1 (2022)**: High- and low-frequency observational methods and models to comprehensively investigate processes susceptible to climate and anthropogenic change integrated. **M4.3-2 (2023)**: Development of an intelligent swarm of AUVs for small-scale observations finished. **M4.3-3 (2025)**: Parameterization of sub-mesoscale energy transfer for larger-scale ocean models available.

Infrastructures and specific resources. Infrastructure includes COSYNA/DANUBIUS Elbe MOSES facilities, the long-term observatories at the AWI coastal stations Helgoland and Sylt, and North Sea (e.g. PANGAEA), AWIPEV/COSYNA Station (Svalbard) and the Herschel Island Qikiqtaruk Observatory (Western Canadian Arctic). Together with external partners, additional observatories could be tackled during the Program such as the new BEAGLE Channel Observatory (Patagonia). Research vessels (RV) Uthörn, Heincke, Mya, Prandtl underpin experimental work in European sites, RV Polarstern in polar seas. High-resolution observation capability (plane, small vessels, AUVs) enable analyses of small-scale phenomena. Partners operate state-of-the-art laboratories (including the MICADAS Radiocarbon Dating Facility at AWI), and a coastal node (Helmholtz Coastal Data Center, HCDC, at HZG) of a national science data structure, which complements the modeling infrastructures mentioned in the other STs.

Cooperation partners. Leuphana University (participation at ISC-3) and the MARE:N coastal research project consortia. Coastal observations are embedded in DANUBIUS-RI community, COPERNICUS, JERICO, GEOTRACES, and NUNATARYUK, DFG Collaborative Research Centre 'Energy transfers in atmosphere and ocean' for sub-mesoscale processes. Across-scale models are developed with VIMS and SIO and with key partners such as IOW in Germany, Europe and overseas.

Risks and Opportunities arise from the progression from fundamental processes of energy fluxes and matter cycles across coastal compartments and scales (ST4.1) to the system's approach in ST4.2. It ambitiously links the past to the future in the analysis of ecosystem functioning, yet it is entirely feasible. To develop options for sustainable resource-use and development of coastal zones (ST4.3) from the two first STs is an urgent need, and opportunities take root in successful climate service approaches as blueprints for actionable information. Operational risks in developing novel methods, techniques, and of operations under harsh conditions are offset by the prospective benefits of the approach that links land to sea in regions differing in climate change and human footprint.

Subtopic 4.2 Coastal system sustainability against the backdrop of natural and anthropogenic drivers

Maarten Boersma, AWI; Corinna Schrum, HZG

Scope and challenges. Coastal systems face a plethora of different **natural** and **anthropogenic** stressors, usages and demands (summarized as drivers), which together impact the **geophysical environment, biogeochemical cycling** and **organisms** in a multitude of complex inter-linked ways. As interactions between drivers are often **non-linear**, the combined effects of these multiple drivers are virtually impossible to explain and predict from our current understanding of linear superposition. This necessitates research focusing on **multiple** drivers in a **temporally dynamic** environment with complex communities. As these interacting drivers manifest across multiple physical and biological scales, from shifting atmospheric conditions, hydrographic and morphodynamic changes to ecosystems and species changes, the interdisciplinary approach pursued in this ST is crucial. We will focus on the effects of multiple natural and anthropogenic drivers on the functioning of coastal ecosystems in temperate and polar coastal areas. We will in particular use the long-term knowledge accumulated for our areas of foci and the information gathered from long-term data and previous research programs as a fundament for the evaluation of the effects of future change. Ecosystem impacts will be studied at different levels of complexity ranging from within-individual scales, using appropriate -omic approaches, to between-species scales (ecological stoichiometry, trophic interactions, and biodiversity), through to complete ecosystems.

Main objectives. The mission of ST4.2 is to provide the knowledge base on the impacts of natural and anthropogenic drivers on coastal systems, addressing three objectives:

- The elucidation of **variability** and **change** of different drivers on a recent time scale, the documentation of change under varying scenarios up to 2100, and the identification of prediction potential.
- The quantification of **cumulative** and **interactive impacts** of drivers on all levels of ecosystem organization, from entire ecosystems to subcellular and genetic make-up of organisms and the development of capacities to **forecast** the impacts of these drivers (e.g., tipping points).
- The identification of **opportunities** and **risks** of human resource use in coastal systems, the definition of sustainable use strategies, the transfer of knowledge and technology to support the management of coastal systems and to espouse their sustainable use (ST4.3).

Work program. Regional climate variations on a multitude of time scales are strong drivers for coastal systems and modulate, together with direct human impacts, coastal marine ecosystem structure and productivity. The assessment of past, ongoing and future coastal climates is based on three avenues: the reconstruction and analysis of **past** environmental conditions on multi-decadal to multi-centennial time scales, the development of scenarios for possible **future** changes under changing climate and anthropogenic forcing, and the identification of **predictability** potentials on seasonal to decadal time scales.

Focusing on the last two millennia, past climates will be reconstructed by using a combination of proxy records (sediments, trees, coastal dunes, human archives) and regional and global climate- and physical-biogeochemical models[138] (link to CTA ESM) in combination with sophisticated data science and artificial intelligence methods, including machine learning and deep learning (link to HAICU). Integrating multi-decadal to centennial reconstructions will allow an assessment of external climate forcing impacts on climate variations on regional scales. This will provide an independent data-based product to assess climate models' performance to simulate regional climate changes (link to T2) and will support climate projections and seasonal to decadal climate predictions that can be used to assess future climate impacts on coastal ecosystems. Geological records that complement time-series of measured environmental data will be used to link past climates with biological communities, thus supplementing our current knowledge on the variability and resilience of key habitats. We will reconstruct these paleo coastal habitats using paleo-ecological and paleo-environmental proxies (foraminifera, diatoms, stable isotopes) from sediment cores (link to T2 and T5). Advances in ancient DNA research offer the possibility to retrieve information on community assemblages of the past.

The recent biological past will be described using our unique long-term data series and our knowledge from previous LTER research including rare biodiversity data sets, ranging back 50–100 years in European waters[139] and 25 years in polar systems, supplemented by model-based regional reconstructions. We will employ a combination of taxonomic and functional metrics to characterize changes in biodiversity, identify shifts in community structure, relate these to ecosystem functioning, and link all of these to natural and anthropogenic drivers. Shifts in drivers affect the spatial distribution of populations and may lead to changes in key traits, mediated, for example, by species leaving or entering a given system.[140] Alternatively, specific ecosystem

[138] *Gómez-Navarro JJ, Zorita E, Raible C, Neukom R. 2017. Pseudo-proxy tests of the analogue method to reconstruct spatially resolved global temperature during the Common Era. Clim Past. 13(6):629–648.

[139] *Wiltshire KH, Boersma M, Carstens K, Kraberg AC, Peters S, Scharfe M. 2015. Control of phytoplankton in a shelf sea: Determination of the main drivers based on the Helgoland Roads Time Series. J Sea Res. 105:42–52.

[140] *Buschbaum C, Cornelius A, Goedknegt MA. 2016. Deeply hidden inside introduced biogenic structures – Pacific oyster reefs reduce detrimental barnacle overgrowth on native blue mussels. J Sea Res. 117:20–26.

processes may be preserved through replacement by ecologically similar species, despite changing biological communities. Thus, a special focus will be on potential changes or stability in the functional biodiversity of coastal seas through species invasions, extinctions, and reintroductions, and the risks and opportunities these provide. Moreover, changes in natural and anthropogenic drivers also influence acclimation and adaptation to changing conditions both in the short term (through rapid genetic tracking and phenotypic plasticity) and on longer, evolutionary, time scales.[141] By studying eco-evolutionary feedback loops, we will quantify how these processes alter functional traits within populations and determine to what extent coastal organisms can adapt to changing environmental conditions[142] (in close cooperation with T6).

We will develop future scenarios for key regions, providing coastal sea level scenarios (link to T2), assess the impacts on morphodynamics and coastline changes and coastal biological communities. These scenarios provide input for climate services to assess risks for society and to enable the development of adaptation options (ST4.3). The unanswered question on whether or not natural sedimentation in the Wadden Sea can keep pace with sea level rise represents one of the most pressing issues in the research agenda for this region and its World Heritage Site.

We will also identify how shifting hydrography and terrestrial matter transport, especially in the Arctic nearshore zone (permafrost melting) will affect the composition and functioning of coastal communities. Impacts of interacting anthropogenic and natural stressors and drivers on genes, individuals, and communities will be investigated using a wide range of experimental approaches. Space-for-time approaches will allow the identification of the evolutionary potential in key species. Experiments ranging in scale from single species to large communities and natural comparisons will allow, on the one hand, a proper prediction of future situations given different scenarios, and, on the other hand, the disentanglement of the importance of the different drivers. Field, mesocosm, and laboratory experiments will manipulate multiple stressors in order to provide a holistic representation of future conditions in coastal ecosystems. State-of-the-art infrastructures allow experiments at a scale relevant to the specific species interactions (trophic, competitive, parasitic and mutualistic) and food web stability. These experiments will provide the information needed to predict the potential restructuring of biological communities at the ecosystem scale and the associated shifts in coastal ecosystem functioning. For this research, we will concentrate on both prokaryotic and eukaryotic plankton, on nekton, and benthic ecosystems such as seagrass and macroalgal beds, oyster reefs, and cold-water corals.

Using ecological network analyses, we will determine how stable and resilient coastal biological communities are towards changes in natural and anthropogenic drivers (link T6). This will enable us to quantify their robustness and vitality and to test the role of certain keystone species within these systems. We will further integrate our findings on the impacts of climate variability, change and anthropogenic drivers on coastal ecosystem with the help of coupled high-resolution coastal models for atmosphere, waves, hydrodynamics, marine benthic and pelagic biosphere and terrestrial hydrosphere in combination with advanced individual-based and end-to-end ecosystem[143] models and empirical data analysis for selected coastal and estuarine systems. New, trait-based approaches will enable a prediction of multiple stressor impacts based on function rather than identity of species. This integrated analysis of the structural and functional properties of coastal ecosystems will provide information on the potential alterations of the goods and services provided to human society. Translating changes in the functioning of different trophic groups into indices directly related to ecosystem services (such as nutrient turnover, provision of food to higher trophic levels, and carbon sequestration/export), will provide a base for management decisions. Gained process understanding (ST4.1) will be used to support the development of sustainable future scenarios considering climate and human interventions (with ST4.3).

Integration of the approaches detailed above will be achieved with a special focus on the impacts of direct human interventions on coastal spaces (Fig. 4.4). We will study the implications of especially growing offshore

[141] *Shama LNS. 2015. Bet hedging in a warming ocean: predictability of maternal environment shapes offspring size variation in marine sticklebacks. Glob Change Biol. 12:4387–400.

[142] *Wendling CC, Fabritzek AG, Wegner KM. 2017. Population-specific genotype x genotype x environment interactions in bacterial disease of early life stages of Pacific oyster larvae. Evol Appl. 10:338–347.

[143] *Heymans JJ, Skogen M, Schrum C, Solidoro C. 2018. Enhancing Europe's capability in marine ecosystem modelling for societal benefit. In: Larkin KE, Coopman J, Muñiz Piniella A, Kellett P, Simon C, Rundt C, Viegas. C, Heymans JJ, editors. Future Science Brief 4 of the European Marine Board. Ostend (BE). p 32.

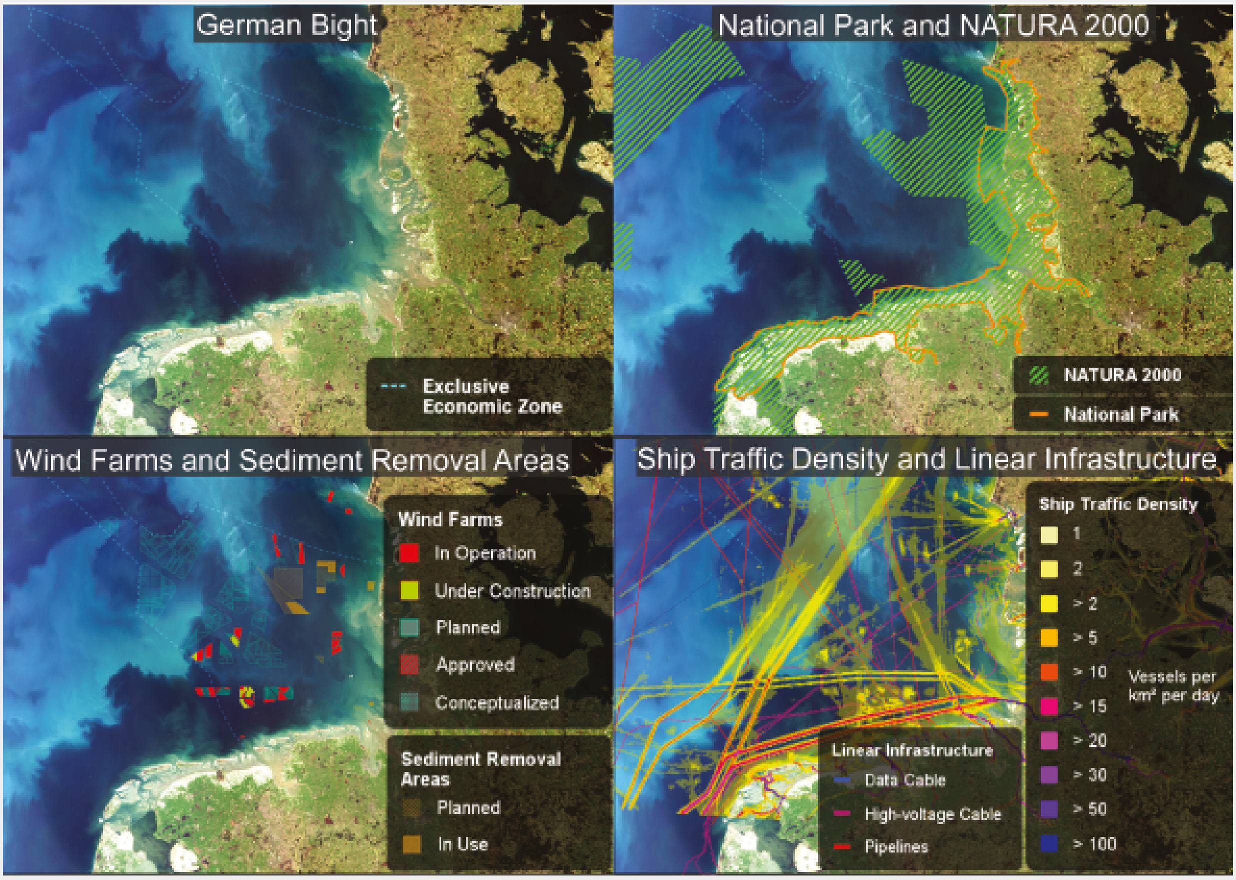


Fig. 4.4: German Bight Marine Spatial Planning and multiple use of coastal spaces (source BSH and HZG; https://coastmap.hzg.de/coastmap/tools/coastmapAPP/).

wind farming and marine energy production in a holistic approach integrating physical, chemical and biological changes and their interaction on various spatial and temporal scales using advanced coastal modeling capacity, experiments, and observations. In marine regions generally devoid of hard structures, the potential ecological importance of sub-marine structures is very high but poorly investigated. Here, we will concentrate on the effects of a range of different biogenic and anthropogenic structures and use our combined expertise to assess their importance. These include oyster beds in temperate regions, Arctic kelp forests, and cold-water coral reefs as well as those that have been introduced by humans, such as wind farms, oil rigs, or coastal armoring. We will contrast the impacts of these hard, permanent, structures with more ephemeral ones such as fronts and eddies (Link to ST4.1). By contrasting structures of different nature and age and employing scenario modeling combining future scenarios for climate and anthropogenic impacts, we will be able to evaluate the effects of future changes in our coastal seas, both as a result of ongoing building and re-introductions of reef-building species such as the European oyster[144] in the context of nature conservation and multiple use of these structures (Link to ST4.3).

Deliverables (D) and Milestones (M)

- **D4.4 (2027):** High-resolution reconstruction of regional climate and ecosystem change for the last two millennia. **M4.4-1 (2024):** High-resolution reconstruction of past 70 **(2022)** and 150 years **(2024)** climate for the European shelf. **M4.4-2 (2025):** Reconstruction of species and population changes on centennial time scales. **M4.4-3 (2026):** Reconstruction of ecosystem changes for the last two millennia for key regions.
- **D4.5 (2027):** Coastal sea level information for coastal zone management for northwestern European coasts and Arctic shelves and small islands. **M4.5-1 (2024):** Local scenarios for sea level change on 30,

[144] *Pogoda B. 2019. Current Status of European Oyster Decline and Restoration in Germany. Humanities. 8(9):1–12.

50, and 80 years' time scales for these European coasts. **M4.5-2 (2025):** Decadal predictions for sea level changes on local and coastal scales.

- **D4.6 (2027):** Assessment of multi-driver impacts on coastal communities. **M4.6-1 (2024):** Identification of the responses of selected keystone species. **M4.6-2 (2026):** Finalization of community experiments and observations. **M4.6-3 (2026):** Integration of experiments with coastal ecosystem models.
- **D4.7 (2027):** Predictive capacities for climate and human impacts on coastal ecosystems considering different management options. **M4.7-1 (2024):** Predictive potentials for regional climate impacts to coastal systems on different time scales uncovered. **M4.7-2 (2026):** Scenarios for key estuarine systems, integrating climate, land use, coastal protection, and infrastructure development. **M4.7-3 (2026):** Future scenarios for climate, offshore resource utilization, shipping, important pollutants, and land use changes for the Northwest European shelf ecosystems.

Infrastructures and specific resources. This ST is relying heavily on the experimental coastal infrastructure and long-term observations mentioned in the other ST as well as on regional and global high-resolution climate data such as the coastDat model database, dynamically compiled climate data and worldwide available paleoclimate and paleoenvironmental records of the past centuries. Crucial is the Geesthacht Coastal Model Framework (GCOAST part of the CTA ESM framework), which will be further advanced into a national coastal modeling infrastructure. The ST hosts the support infrastructure of the local hub Artificial Intelligence in Earth System Analytics and Modelling of the Helmholtz Artificial Intelligence Cooperation Unit (HAICU), which will develop the potential for supervised and unsupervised learning in Earth System Research. Critical are the HPC infrastructures such as the cluster OCEAN II and DKRZ.

Cooperation partners. Close collaborations in ecosystem research and modeling have been established, among others, with the University of Hamburg, the Institute of Baltic Sea Research, Ifremer (experimentation) and SAHFOS and MBA (time-series). Activities in ST4.2 are embedded in international networks and multilateral networks such as the Trilateral Wadden Sea Cooperation.

Risks and Opportunities. The biggest opportunity of this ST is to truly integrate experimental research on ecosystem function as influenced by a multitude of environmental drivers, carried out at a wide variety of different scales with novel modeling approaches, yielding unprecedented predictive power on the functioning of ecosystems in different futures. At the same time, this is also a risk. Upscaling results obtained at lower levels of integration to biological communities and ecosystems has proven challenging. However, as we also aim to carry out experiments at the level of the ecosystem, the risks are not high.

Subtopic 4.3 Sustainable resources-use, adaptation, and urban systems under global and climate change

Bela H. Buck, AWI; Louis Celliers, HZG

Scope and challenges. ST4.3 inspires climate services and product development for current and future human activities and sustainable development of coastal regions and its associated marine resources. The ST proposes science-society innovation to support cross-sectoral management in priority sectors such as water, food production (marine aquaculture), and energy. It also advances the generation and integration of data and information for climate change adaptation. Science-based decision-making requires innovative tools, methods, and frameworks that can facilitate and guide coastal management, which represent all relevant components including climate, resource use (e.g., marine aquaculture), hydrology, soils, forests, ecosystems, economy, and (marine and urban) spatial planning. Pressing questions on multi-use of coastal spaces and marine resource use also have a temporal component as their underlying drivers may be influenced by climate change. Knowledge from long-term studies and data will act as a basis for the evaluation of the effects of future change on the needs of the stakeholders, for example in terms of fisheries. Linking present and future states of key components of the coastal and shelf sea systems will be achieved by integrated regional modeling systems.

Main objectives. This ST addresses fundamental questions important for human society such as: How do we retain, enhance and transform coastal functions and resources and sustainable livelihoods (both blue and green economy principles), in a safe operating space where people and coastal ecosystems can prosper?[145] How do human communities transition from coping to thriving, given the threats and opportunities associated with environmental and climate change? ST4.3, therefore, proposes four objectives:

- Explore human interactions with environmental goods and services of coastal and marine ecosystems in order to develop management strategies in combination with new solutions for conservation, and sustainable coastal and marine resource use.
- Develop strategies to enhance sustainable coastal and marine resource use and management, by drawing on technological, biological, socio-economic approaches (compliant with the standards of the Food and Agriculture Organization of the United Nations, FAO) while following guiding principles for the protection of coastal and marine habitats and species.
- Establish coastal urban observatories and develop experimental approaches to transfer scientific knowledge to society.
- Design and establish innovative tools and toolkits, methods, services approaches, and trans- and interdisciplinary processes that can facilitate and guide both incremental and transformative adaptation (and mitigation) of coastal areas and in particular coastal cities.

Work program. The work program enables us to work on the coastal system but also on its components (Fig. 4.5). Coastal and shelf sea systems provide goods and services, which benefit society, but the current use-patterns (e.g., fisheries, tourism, energy) are often de-coupled from conservation targets. Therefore, scientific ecosystem approaches are essential, which include comprehensive studies on ecological, economic, and social needs for sustainable resource-use. This will be done in collaboration with key societal actors, in order to fill information gaps, respond to opportunities, and address societal challenges. Innovative management strategies will be combined with new, ecosystem-friendly technology approaches to reduce the ecological footprint of human interventions. At the same time, those approaches will help to build climate-resilient coastal areas. Newly developed strategies and technologies reach stakeholders through efficient knowledge and technology transfer, including other applied and fundamental fields.

Fig. 4.5: Coastal system and its components from Schultz-Zehden et al. 2018.[146]

[145] Nash KL, Cvitanovic C, Fulton EA, Halpern, BS, Milner-Gulland EJ, Watson RA, Blanchard JL. 2017. Planetary boundaries for a blue planet. Nat Ecol Evol. 1:1625–1634.

[146] *Schultz-Zehden A, Lukic I, Onwona Ansong J, Altvater S, Bamlett R, Barbanti A, Bocci M, Buck BH, Calado H, Varona MC, et al. 2018. Ocean Multi-Use Action Plan, MUSES project. Edinburgh (GB). 132 p.

The **efficacy of area-based management tools such as Marine Protected Areas** (MPAs) is well established. Other Effective Conservation Measures (OECMs) such as offshore wind farms can interact with 'classical' MPAs. The co-location of marine protected areas, aquaculture and commercial fishing, in particular, creates opportunities to ease demands on ocean space, reduce conflict, and minimize the environmental impact.[147] We will investigate the development of ecological functioning within offshore wind farms and MPAs to compare potential changes with non-protected sites in the North Sea and how that informs global good practice for area-based management approaches. Additionally, we will develop sustainable management guidelines for MPAs and OECMs to combine restoration needs, multiple-human use, and marine ecosystem services in a high-CO_2 world.[148]

Food security, human health, and human welfare are jeopardized by unsustainable extraction of living marine resources. The relationship between marine resource use and the SDGs (especially goals 2, 13, and 14) is not yet well elaborated. As a result, we will **capture the dimensions of the SDGs in transformative marine resource use** (in cooperation with T6 and T7). This Subtopic also intends to provide scientific evidence for zero nutrient-discharge and sustainable aquaculture (in close collaboration with ST4.2). This includes the development of strategies for Integrated Multi-Trophic Aquaculture (IMTA)[149] and other eco-system friendly strategies (using the coastal pollution toolbox of ST4.1) and the design of robust technology (Technology Readiness Level 6 and above) in high-energy environments. This is aligned with the objectives of T7 on bioeconomy.

The restoration of marine plants and use as **nutrient-extracting organisms** is considered an important strategy for the reestablishment of ecosystem services ('global carbon, nutrient, and trace element budgets' from ST4.2). Restoration strategies for a successful recovery require **long-term ecological research on sensitive species.** Together with ST4.1 and ST4.2, we will combine basic research on endangered species and habitats with the needs and obligations of national and international conservation authorities.

Marine spatial planning (MSP) and ocean zoning can offer a **structured and intentional multi-use of ocean space and infrastructure.**[150] This requires a fundamental understanding of the impacts of human actions on marine ecosystems (ST4.2) and the role and drivers of social interactions of key actors. Sustainable and space-efficient resource-use scenarios based on cumulative impact assessments will be developed in collaboration with actors from society, regulatory bodies, companies, and policy as well as other natural and technical science institutions.

Conducting regional to local climate model projections (e.g., WCRP-CORDEX)[151] are the basis for scientifically sound climate information. In combination with innovative methods such as participatory group modeling approaches and systems modeling, societal actors and scientists will co-design and co-create **regional integrative modeling frameworks.** Such model frameworks are composed of relevant components (e.g., climate, hydrology, economy, urban areas, energy (link to HI-CAM), estuaries, spatial planning) of complex coastal systems with the aim of simulating the impacts and benefits of management and policy measures for coastal urban environments. The modeling frameworks will inform the management and planning of future states of the coasts under different warming scenarios. This approach will use comparative case studies in cooperation with ST6.2 and data provided by ST4.2 and, where regionally relevant in case studies, from ST6.4.

The regional modeling frameworks will provide the scientific basis for the development of **modular planning and adaptation toolkits, guidelines, and decision-support systems** for urban coasts.[152] These activities support the development of a land management toolkit (link to T5). For coastal cities, it also incorporates the

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[147] Di Tullio GR, Mariani P, Benassai G, Di Luccio D, Grieco L. 2018. Sustainable use of marine resources through offshore wind and mussel farm co-location. Ecol. Modell. 367:34–41.

[148] Rau GH, McLeod EL, Hoegh-Guldberg O. 2012. The need for new ocean conservation strategies in a high-carbon dioxide world. Nat Clim Change. 2:720–724.

[149] *Buck BH, Troell M, Krause G, Angel D, Grote B, Chopin T. 2018. State of the art and challenges for multi-trophic offshore aquaculture. Front Mari Sci. 5(165):1–21.

[150] *Schupp MF, Bocci M, Depellegrin D, Kafas A, Kyriazi Z, Lukic I, Schultz-Zehden A, Krause G, Onyango V, Buck BH. 2019. Towards a Common Understanding of Ocean Multi-Use. Front Mari Sci. 6(165):1–12.

[151] *Jacob D, Petersen J, Eggert B, Alias A, Christensen OB, Bouwer LM, Braun A, Colette A, Déqué M, Georgievski G, et al. 2014. New high-resolution climate change projections for European impact research. Reg Environ Change. 14(2):563–578.

[152] *Cortekar J, Bender S, Brune M, Groth M. 2016. Why climate change adaptation in cities needs customized and flexible climate services. Climate Services. 4:42–51.

needs of the private sector (marine aquaculture, water, energy, tourism, etc.) and coastal infrastructure planning. The design of 'coastal toolkits' incorporates knowledge from ST4.1 (catchment prioritization schemes, pollution toolbox, etc.) and ST4.2 (sea level rise, ecosystem modeling). A strategy towards the establishment of a virtual Center of Excellence for Climate and Coastal Services will be developed. Such a center fosters long-term cooperation to synthesize scientific outputs, to co-develop solutions, and to increase societal impact.

Climate services will be developed to become 'transformational' given the approaching 1.5°C global warming.[153] The convergence of climate action (adaptation and mitigation), disaster risk reduction and sustainable development are key for overcoming societal barriers and to create conditions to limit global warming. ST4.3 will **support climate adaptation policy** (e.g., UNFCCC National Adaptation Plans) by developing climate services for national, sub-national and local coastal adaptation. Coastal Living Laboratories[154],[155] including the Wadden Sea are proposed in ST4.3 as 'test-beds' for social and technological innovation. These will be developed along sectoral axes (aquaculture, energy, water, planning) and in area-based management approaches (marine spatial planning, integrated coastal management, and MPAs). Here the knowledge from long-term studies and previous projects will be integrated with new ocean-climate data in to the evaluations on coastal climate-change adaptation and climate-smart management of coastal areas for the state of coasts in 2050.

Climate services will be further advanced by applying **novel data science for data exploration**. By using tools such as machine and deep learning methods and virtual reality technologies, we will generate spatially explicit, actionable information to support coastal governance planning, management, and climate adaptation strategies. Finally, the 'services approach' is inherently trans- and interdisciplinary. The experiences with **participatory modeling, stakeholder engagement, and co-creation**[156] are producing many examples of good practices to support science-based policies. The ST will apply transdisciplinary research approaches and will further develop evaluation schemes for climate services.

Deliverables (D) and Milestones (M)

- **D4.8 (2027):** Prototype decision-support tool for developing multi-use scenarios established. **M4.8-1 (2023):** Regional integrative modeling frameworks for two demonstration regions available. **M4.8-2 (2023):** Develop sustainable management guidelines focusing on ecosystem parameters for MPAs and OECMs. **M4.8-3 (2024):** Develop strategies for integrated risk management and spatial planning. **M4.8-4 (2025):** Cumulative socio-ecological impact assessments for multi-use concepts published to support decision-makers, sustainable blue growth initiatives, and conservation efforts. **M4.8-5 (2026):** Platforms to integrate high-resolution atmosphere-ocean climate change simulation results with socio-economic and environmental data for impact modeling established.
- **D4.9 (2027):** Framework for transformative marine resource use developed capturing the dimensions of the SDGs. **M4.9-1 (2023):** Concepts for zero-discharge from sustainable aquaculture developed, including IMTA/other eco-system friendly strategies and robust technology for high energy environments. **M4.9-2 (2025):** Restoration strategies for macroalgae and nutrient extraction capabilities of marine plants following ecosystem services developed.
- **D4.10 (2027):** Strategy for a virtual Center of Excellence for Climate and Coastal Services developed to support transformative adaptation and sustainable coasts in 2050. **M4.10-1 (2024):** Coastal management toolkit implemented, and prototype of coastal climate services developed. **M4.10-2 (2026):** Catalogs of climate and coastal services for sustainable urban coasts and settlements published.

Infrastructures and specific resources. In addition to HPC facilities, this ST relies on large observational infrastructure, including COSYNA, DANUBIUS-RI, MOSES, and various AWI stations. The research centers on Helgoland, Sylt and in Bremerhaven (Centre for Aquaculture Research) are key infrastructures, as are the research vessels, Heincke, Uthörn, Mya, Aade, and the large mesocosm 'REEPON'.

[153] *Jacob D, Kotova L, Teichmann C, Sobolowski SP, Vautard R, Donnelly C, Koutroulis AG, Grillakis MG, Tsanis IK, Damm A, et al. 2018. Climate impacts in Europe under +1.5°C global warming. Earth's Future. 6(2):264–285.

[154] Living laboratories are user-centered, open-innovation systems that integrate research and innovation processes.

[155] Kronsell A, Mukhtar-Landgren D. 2018. Experimental governance: the role of municipalities in urban living labs. Eur Plan Stud. 26:988–1007.

[156] *Ojwang L, Rosendo S, Celliers L, Obura D, Muiti A, Kamula J, Mwangi M. 2017. Assessment of coastal governance for climate change adaptation in Kenya. Earth's Future. 5:1119-1132.

Cooperation partners. Academic and non-academic partners at the science-society interface covering a variety of natural and socio-economic and systems thinking expertise are important. They include, academic institutions (e.g., Technical Univ. Hamburg, Univ. Hannover, Thünen Institute for Sea Fisheries, Scottish Association for Marine Science), international research networks (e.g., EURO-CORDEX) for expertise in climate modeling, international networks (e.g., the Wadden Sea Forum, Climate Services Partnership, Future Earth) and cities (e.g., Bremerhaven), and business companies to integrate practice into climate service development.

Risks and Opportunities. ST4.3 applies strong inter- and transdisciplinary research approaches on all societal levels, including policymakers, businesses, and the general public in relation to the themes mentioned. The communication of uncertainty of scientific findings and the differences between scientific and decision-making time frames can slow down the achievement of the Subtopic objectives. On the other hand, the novel approaches in ST4.3 have the exceptional opportunity to better connect the international framings such as the Sendai Framework, the Paris Agreement, the UN Decade of the Oceans, and the SDGs to inform and guide action on the local level through cultivating systems thinking in a unique manner.

E) Previous achievements of the contributing centers and infrastructures

Expertise and preliminary work. HZG/IfK focuses explicitly on geophysical and chemical coastal research and has 10-years of expertise in coordinating and running the coastal observing system COSYNA.[157] It is leveraged by the modular observing capability MOSES and the coming ESFRI-infrastructure DANUBIUS-RI. HZG/IfK has extensive experience with high-resolution observations and led large sub-mesoscale experiments in California and the Baltic Sea. Milestones of work in pollution and eutrophication have been the generation and compilation of data sets of novel pollutants, atmospheric pollution, seafloor properties and ecosystem services (e.g., eutrophication mitigation) in European and Asian seas, and leading interdisciplinary consortia in support of national and international directives. HZG/IfK has in-depth expertise in coupled regional Earth system modeling, including distinguished developments for coupling ocean, waves and atmosphere,[158] hydrology and novel concepts for the marine biosphere and ocean sediments. HZG/IfK has outstanding expertise in reconstructing and analyzing high-resolution regional and global past climate, using a combination of regional and global models, long observational records, paleoclimate proxies as well as statistical and advanced data science methods.[159] It hosts the Northern German Coastal and Climate Office and led the publication of several regional climate change reports,[160] which builds the basis for future strategies by HELCOM, regional and national governments, and agencies.

HZG/GERICS is an international trendsetter in developing new integrated concepts and practices for climate services. It interacts with society, engaging policy, science, and business. HZG/GERICS has leading roles in WCRP CORDEX, Earth League, Climate Service Partnership, and IPCC,[161] and host secretariats in all of them except IPCC. It acts as an observer of the UNFCCC as the main forum where decisions on climate policies are made. The interdisciplinary team builds on world-class expertise in regional and local climate modeling,[162],[163] and excellent competences in environmental and socio-economic sciences.

157 *Baschek B, Schroeder F, Brix H, Riethmüller R, Badewien TH, Breitbach G, Brügge B, Colijn F, Doerffer R, Eschenbach C, et al. 2017. The Coastal Observing System for Northern and Arctic Seas (COSYNA). Ocean Sci. 13:379–410.

158 *Staneva J, Schrum C, et al. 2018. A North Sea-Baltic Sea regional coupled models: Atmosphere, wind waves and ocean, EuroGOOS. In: Buch E, Fernández V, Eparkhina D, Gorringe P Nolan G, editors. EuroGOOS. p. 223–233.

159 *Weisse R, Bisling P, Gaslikova L, Geyer B, Groll N, Hortamani M, Matthias V, Maneke M, Meinke I, Meyer EMI, et al. 2015. Climate services for marine applications in Europe. Earth Perspectives. 2(3):14.

160 *Quante M, Colijn F, editors. 2016. NOSCCA North Sea Region Climate Change Assessment. Berlin (DE): Springer. p.528.

161 *Hoegh-Guldberg O, Jacob D, Taylor M, Bindi M, Brown S, Camilloni I, Diedhiou A, Djalante R, Ebi KL, Engelbrecht F, et al. 2018. Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. p. 175–311.

162 *Pfeifer S, Rechid D, Reuter M, Viktor E, Jacob D. 2019. 1.5°C, 2°C, and 3°C global warming: a new method to detect European regions affected by multiple changes. Reg Environ Change.1–12.

163 *Pietikäinen JP, Markkanen T, Sieck K, Jacob D, Korhonen J, Räisänen P, Gao Y, Ahola J, Korhonen, H., Laaksonen A. 2018.The regional climate model REMO (v2015) coupled with the 1-D freshwater lake model FLake (v1): Fenno-Scandinavian climate and lakes. Geosci Model Dev. 11:1321–1342.

AWI focuses on coastal systems in the North Sea, Arctic, and Southern Ocean. Using observations, experimentation, and modeling, the ecosystem status is evaluated with regard to climate change as well as human-induced eutrophication, pollution, and species community change. AWI's expertise in biological and biogeochemical dynamics of coastal ecosystems is linked across a range of scales and across a wide range of geochemical conditions.[164],[165] Studies at the molecular level link to the organism level via population ecology, and via species interactions to community shifts, functional biodiversity, and food-web dynamics. AWI focuses on disentangling natural ecosystem function and variability from diverse climatic and anthropogenic pressures. The impact of individual drivers has been addressed on a wide range of spatial and temporal scales to assess whether ecosystems, biological communities, species, and organisms can either show resilience and adjust, or succumb to these pressures. The newly founded HIFMB (link T6) will allow to expand this research considerably. AWI contributes to local, regional, national, and international coastal management recommendations, answers stakeholder questions, invests in capacity development, and provides experts for a number of national and international working groups, societal challenges and sustainability questions, for example via the North Sea Office. Members of AWI coast were founding members in the Scientists 4 Future movement.

UFZ investigates all aspects of inland waters, including global water quality assessment. Using advanced monitoring and sensing infrastructures, mobilization, transport, and transformation processes in the catchment-specific functional zones are measured from local to river reach and catchment scale.[166] One focus is on the effect of climate change. UFZ leads MOSES with a focus on heatwaves and hydrological extremes. Catchment wide fluxes of energy, water, and nutrients triggered by extreme events in the Elbe catchment provide a link to the German Bight.

Uniqueness. T4 pursues an ambitious and unique systems approach. This includes observations, their integration into models, the coupling of models, and the development of socially relevant services and products. The Topic is uniquely equipped for this kind of research. HZG and AWI employ experts working across the three STs, and in different compartments and disciplines that are focusing on interactions and couplings in complex coastal environments. Modeling, as well as inimitable observational capacities, have been developed in the past, enabling unique possibilities for improving process and system understanding. This integration of the different expertise and infrastructures allows for a seamless systems analysis from local to regional scales, across different compartments, and from the past into the future.

F) Collaboration and transfer

Partners. To further strengthen excellent coastal and climate research, T4 builds on outstanding strategic partnerships with national and international leading partners. Dedicated activities to complement T4 research are, for example, joint research projects, scientist exchange programs, Ph.D. supervision, and product development.

[164] *Henkel S, Kasten S, Hartmann J, Busso AS, Staubwasser M. 2018. Iron cycling and stable Fe isotope fractionation in Antarctic shelf sediments, King George Island. Geochim Cosmochim Ac. 237:320–338

[165] *Oni O, Miyatake T, Kasten S, Richter-Heitmann T, Fischer D, Wagenknecht L, Kulkarni A, Blumers M, Shylin SI, Ksenofontov V, et al. 2015. Distinct microbial populations are tightly linked to the profile of dissolved iron in the methanic sediments of the Helgoland mud area, North Sea. Front Microbiol. 6:365.

[166] *Wollschläger U, Attinger S, Borchardt D, Brauns M, Cuntz M, Dietrich P, Fleckenstein JH, Friese K, Friesen J, Harpke A, et al. 2017. The Bode hydrological observatory: a platform for integrated, interdisciplinary hydro-ecological research within the TERENO Harz/ Central German Lowland Observatory. Environ Earth Sci. 76 (29).

Table 4.1: Selected key partner of T4 by category (only key partners at the time of writing are presented).

	Key partners	Joint efforts
Academic partnerships (National)	COSYNA Consortium	Integrated observation system.
	DFG Clusters of Excellence CLICCS and 'The Ocean Floor' (MARUM)	Climate research and service; expeditions and field trips in the North Sea.
	KDM / DAM; IOW; DKRZ; MPI-M; HICSS; HIFMB	Coastal carbon transformation, storage marine space; marine and coastal ecosystems, climate change, sea level; high-performance computing; Earth system modeling; climate service science; functional marine biodiversity
Academic partnerships (International)	IOCAS	Environmental pollution
	British Antarctic Survey	Southern Ocean, expeditions, infrastructure.
	EuroGOOS, POGO	Ocean observation
	NIOZ	Marine and coastal ecosystems, climate change, sea level
	NERSC	Ecosystem modeling, carbon cycling, CMEMS.
	CORIANE	Wadden Sea scientific networking
	ICES	Ecosystem science impact human activities
Public Agencies (national)	BSH, BAW, BfG, UBA, German Weather Service, THW	Knowledge transfer, collaborative applied research, development in coupled regional climate, wave and estuary modeling, development of operational methods and services
Transfer and Capacity Building (Public and Private Sector)	WASCAL / SASSCAL; WCRP-CORA; KfW, HPA; SCOR / UNESCO	Development of climate service products, user-friendly climate model; regional climate information; user-driven climate services and products; UNESCO Expert working groups

Positioning of the Topic in international research. T4, in concert with other Topics, leverages and creates synergies between HZG and AWI core expertise and cooperation (KüNO/FONA; COSYNA/MOSES), and international initiatives (POGO, WCRP, DANUBIUS-RI, COPERNICUS, GEOTRACES, JERICO, UN Ocean Decade, Future Earth). It addresses high-level scientific objectives along the coastal agendas of MARE:N, and DAM as national efforts towards sustainable development goals (SDGs 6, 13, 14) and central demands of the UN Ocean Decade. The approach transcends artificial boundaries between sciences and environmental management of land and sea (MSFD, WFD) and will provide the essential knowledge base for integrated use concepts and management of resources in coastal zones. HZG is one of the leading partners of EuroGOOS and participates actively in the regional operational oceanographic for the North and Baltic Sea. HZG is an internationally leading player in reconstructing regional climate on centennial and longer time scales. Through engagement at regional, national, and international levels, HZG/GERICS is shaping the Climate Services Agenda and links the Topic with international initiatives on climate modeling, adaptation, and Disaster Risk Reduction. Since January 2014 UFZ has led the European Topic Centre on Inland, Coastal and Marine waters (ETC-ICM), and has a new mandate from 2019 until 2021. ETC-ICM establishes a seamless environmental information system to assist the EU Commission, the European Environmental Agency (EEA), and EU Member Countries in their attempts to improve the aquatic environment. The unique concentration of coastal expertise in T4 will result in the creation of a virtual Center of Excellence for Climate and Coastal Services, which strives for reaching world-class level.

Cross-Cutting Activities and Alliances. T4 contributes to the CTA MOSES event chains hydrological extremes (led by UFZ) and ocean eddies (led by HZG). CTA MOSES comprises modular, highly flexible, and mobile observation systems for improving our understanding of complex event chains across compartments with strong connections to T2, T5, and T6. The CTA ESM (led by AWI) is targeting the development of coupled models, the assessment of regional extremes, and knowledge transfer to societal actors (links to T1, T2, T3, T5, and T6), and contributes to the development of a national Earth system modeling strategy for climate and coastal modeling. The Geesthacht Coastal Model Framework GCOAST is part of CTA ESM and will be developed towards a national coastal modeling framework within T4.

All T4 partners contribute to the CARF HI-CAM, while HZG coordinates the mitigation cluster 'Net-Zero-2050'. The adaptation cluster is led by UFZ. T4 connections exist to CARF MACE and CARF Resilient Urban Spaces, CTA Digital Earth, CARF REKLIM and is part of the proposed CARF JL-ExaESM, NFDI and Alliance DESA. HZG hosts the local HAICU hub AIM. UFZ coordinates the CTA TERENO hydrological observatory site in central Germany.

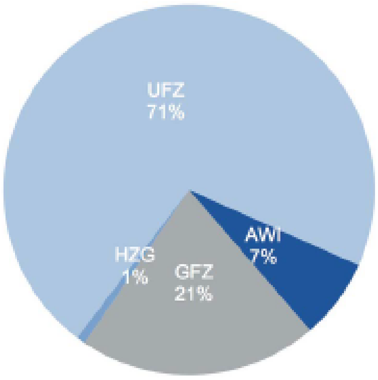
Transfer and contribution to SynCom. T4 will contribute to SynCom with disciplinary and multi-disciplinary knowledge, transdisciplinary research, and evaluation of science-society dialogues pertinent to coasts. The transfer activities include 'science-informs-society' and 'science-interacts-with-society' approaches and builds on the expertise of HZG/GERICS and the regional offices at HZG/IfK (Northern German Coastal and Climate Office), AWI (North Sea Office, REKLIM office), and UFZ (Climate Office for Central Germany). T4 will prioritize co-creation and co-design of knowledge with stakeholders, enhance capacity building, enable technology transfer, employ an open data policy, and provide model data and observations through the coastal data platform HCDC as part of the MareHub of DAM/NFDI4Earth and the DKRZ-CERA-WDCC database. The collaboration with federal, national, and European government agencies and stakeholders will be evaluated to identify information-flow bottlenecks, inefficiencies, and fidelity leading to improved communication channels. To answer needs arising from user-driven questions, management measures, and activities related to the regional to local impact of climate change, all relevant processes and components of the regional coastal system will be assessed. The co-created knowledge will be shared with the general public, national, and international stakeholders through innovative communication channels.

Executive Summary

- T4 applies a unique systems approach to assess coastal transition zones as complex human-environment systems. It integrates a variety of observational facilities, long-term datasets, and natural and socio-economic modeling activities to increase our understanding of coastal systems functioning. It connects land-sea-atmosphere and people as a basis for multi-use scenarios to support solutions towards future resilient social-ecological coastal systems and human livelihood.
- Due to its systems approach, T4 contributes to all objectives of the Program, with a particular focus to objectives 1 (extend predictability), 2 (biogeochemical cycles and fluxes between Earth compartments), 3 (climate change adaptation), 7 (sustainable, climate-resilient marine natural resources), and 9 (interaction between environmental pollution and human and ecological health).
- Placed at the interface of several Earth system compartments, T4 takes a specific role within the Program by integrating modeling activities and observations to improve the overall Helmholtz competence and capacity in Earth system research. Within the Program, T4 has the ambition to bridge the science-society gap by involving societal partners to ensure the development of scientifically sound and relevant solutions for the most pressing issues for coastal zone management.

Topic 5: Landscapes of the Future: Securing Terrestrial Ecosystems and Freshwater Resources under Natural Dynamics and Global Change

Spokesperson: Bernd Hansjürgens, UFZ



The mission of Topic 5 is to develop pathways towards multifunctional landscapes which maintain functioning ecosystems, halt biodiversity loss, and provide fresh water, food, and habitable living spaces as essential resources for humans. Topic 5 focuses on the interplay of human impacts and natural dynamics of landscapes. We aim to provide actionable knowledge and develop societal responses (e.g., governance mechanisms and policy options) for adaptation to climate change, halting biodiversity loss, sustainable agricultural policies, achieving freshwater security, and transforming cities as resilient human-natural systems.

A) Scope and challenge of the Topic

Research subject. Biodiversity, soils, water, and ecosystems[167] are essential functional components of landscapes.[168] Landscapes and their capability of providing resources for humans are rooted in the natural Earth surface system,[169] dynamically connected with geological and atmospheric processes and essential biogeochemical cycles. Worldwide changes to farmlands, forests, and waterways are driven by the rising demand for food, raw material, energy, water, and shelter due to a growing population and increasing footprints of developed societies. Inevitably, landscapes are increasingly impacted by anthropogenic manipulation and pressures.

Pervasive environmental impacts compromise the provisioning of resources and ecosystem services as well as the buffering capacity of landscapes, and with this human life and well-being. Currently, many resources provided by landscapes are depleted faster than they are regenerated. Additionally, they are affected by continuous climate change, which includes the increase in extreme events. The IPCC special report on limiting global warming to 1.5°C (SR1.5) above pre-industrial levels highlights that the frequency and intensity of extreme events have already increased over a time span during which 0.5°C global warming occurred. This has caused both negative impacts on food security and terrestrial ecosystems and contributed to desertification and land degradation in many regions of the world. The impacts will further intensify and become more frequent as warming progresses.[170]

[167] We define 'ecosystems' as interacting systems of communities of organisms and their environment.

[168] We define 'landscapes' as coherent terrestrial systems with natural and anthropogenic features.

[169] We define 'Earth surface system' as the land in its interactions with other spheres.

[170] IPCC 2018. Special Report: Global Warming of 1.5°C: Summary for Policymakers; IPCC 2019. Special Report: Climate Change and Land: Summary for Policymakers.

As a result of competing societal demands for resources and increasing pressures, there is a growing potential for conflict between various environmental and societal goals – as reflected in trade-offs between the UN's Sustainable Development Goals. Landscapes need to provide multiple functions that human societies require despite potentially conflicting objectives. There is an urgent need for finding new pathways that sustainably balance, for example, agriculture, nature conservation, freshwater management, and connected urban livelihoods.

Viable multifunctional landscapes of the future must be able to sustainably deliver the many and diverse services demanded by society, even under intensifying pressures. They have to retain enough of their natural capacities in order to safeguard the multiplicity of services, their role in biogeochemical processes of the Earth system, and regulate the climate. They must sustain food production, maintain fresh water and forest resources, provide energy, render urban areas livable, and they have to be resilient to hydrometeorological extremes.

The challenge is to balance these diverse landscape functions by exploiting synergies and minimizing trade-offs. To this end, we have to i) understand complex environmental processes and their interactions against the backdrop of natural dynamics, socio-economic drivers, and decision-making procedures, ii) assess environmental impacts of resource use on human and ecosystem health, and iii) develop strategies and provide actionable knowledge[171] on how multifunctional landscapes can be achieved.

Topic 5 (T5) comprises all these elements to adopt an advanced and novel systemic perspective on landscapes. This means to integrate environmental compartments, time scales, and socio-economic sectors, and match natural functions of the Earth's terrestrial surface with functions that are marked by human use, i.e., consumption, alteration, and degradation. Our approach is built on experiments and observations, and on reconstructions of Earth surface dynamics during periods of rapid climate change, leading to an in-depth understanding of how terrestrial ecosystems and freshwater resources respond to changing pressures. Resulting impacts are analyzed for past trajectories, observed at current states and modeled for future pathways.

All this feeds into a new generation of high-resolution predictive models and their implementation into a modular land simulator. The central synthesis product LandTrans, to which all Subtopics (STs) will deliver inputs, will permit the design of sustainable management options. It will comprise scenarios, data products, and a suite of adapted process-based and data-driven models. These models will be used, in collaboration with stakeholders, to identify suitable policy interventions, governance options, leverage points, and management strategies. It will picture best-practice societal transition pathways towards multifunctional landscapes, including urban spaces and the urban-rural nexus.

Explanation and justification of research. T5 addresses five closely linked research subjects to fulfill its mission:

1. Terrestrial ecosystems of the future: **Securing ecosystem functions and biodiversity.**
2. Water resources and the environment: **Securing freshwater resources.**
3. Natural dynamics of the terrestrial Earth surface system: **Determining natural functions and sensitivities of the Earth surface system.**
4. SMART models and monitoring: **Providing robust projections.**
5. Society and the terrestrial environment: **Making multifunctional landscapes and resilient cities.**

Securing ecosystem functions and biodiversity: Halting and reversing ecosystem degradation and biodiversity loss by exploring and designing solutions for sustainably managing ecosystems and landscapes that provide the needs of people and nature.

Expansion and intensification of agriculture and forestry, urban sprawl, and climate change are the major drivers that influence biodiversity, soils, and ecosystems. The focal question is how ecosystem functions and terrestrial biodiversity can sustainably be maintained or even restored. Developing scenarios and pictures of the future that address this focal question requires expanding our current knowledge of global change to include interactions between biotic and abiotic processes and socio-ecological feedbacks, and requires explicit consideration of non-linearities in trends of ecosystem states and functions across different spatial and

[171] "Propositions that are actionable are those that actors can use to implement effectively their intentions. Actionable knowledge requires propositions that make explicit the causal processes required to produce action." Argyris C. 2005. Actionable Knowledge. In: Knudsen C, Tsoukas H, editors. The Oxford Handbook of Organization Theory.

temporal scales. We fill empirical knowledge gaps with experiments, observations, and distributed networks across regional and global scales, and incorporate novel technologies to improve the precision and efficiency of this research. We aim to deliver actionable, policy-relevant knowledge, including landscape management tools for decision-makers and stakeholders and biodiversity action plans (e.g., for pollinators), thus for halting and reversing the loss of biodiversity and degradation of soils.

Securing freshwater resources: Identification of trajectories towards clean and safe water resources for human demands, and risk reduction of hydrological extremes without compromising ecosystem health.

Water is a fundamental resource for multiple human demands, such as drinking water supply, food production, and energy provision. Pressures and impacts are causing water quantity, water quality, and aquatic biodiversity to deteriorate, and hydrological extremes are impacting many regions of the world. The expected expansion of urban areas and agricultural intensification will further alter regional water cycles, and all these dynamics will be accompanied by regionally varying climate change patterns. At the same time, policies at national, European, and global levels will likely drive increased resource and interlinked water consumption. Efforts to achieve water security can only be effective if an integrated hydrological, ecological and socio-economic approach is taken that addresses the whole water cycle, and critical trade-offs between the competing human water use and ecosystem demands, in solution-oriented ways. Historical, current, and future basin trajectories of water quantity, quality, and aquatic ecosystem functioning under global and climate change will be determined based on a mechanistic and quantitative understanding of the underlying processes. This approach is unique as it will cover entire water cycles from regional to global scales, a wide variety of hydro-ecological settings and a wide spectrum of societal and government types. It will thus decipher the role of water for securing multiple landscape functions.

Determining natural functions and sensitivities of the Earth surface system: Identifying and quantifying the impacts of climate change on sensitive natural elements of terrestrial surface systems, including permafrost ecosystems, and their mechanisms, thresholds, and time scales.

Developing strategies to foster multifunctional landscapes requires a deep understanding of the processes in the lithosphere, hydrosphere, cryosphere, and biosphere that shape the Earth's terrestrial surface, and their links with atmospheric processes. Knowing what determines the stability of the Earth's surface system, and what are the necessary and sufficient conditions for important system change to occur, is essential. Some terrestrial surface systems are robust and stable in the face of strong climatic pressures, while others, such as permafrost systems, are sensitive to minor external changes. Our research will explore and constrain the mechanisms of links and feedbacks between climate, tectonics, landscapes, and biota, with a strong emphasis on the sensitivity of terrestrial surface systems to climate change. It will combine both monitoring and modeling of Earth surface processes and climate interactions on time scales from process events to major secular and cyclic trends on geological time scales, and reconstruction of past processes recorded in deep time archives. This will help anticipate the impacts of future global and climate change and reduce uncertainties. Crucially, we will distinguish, where possible, the changes driven by human activity from those inherent to Earth's natural system behavior, to help the research objective of T5; namely, to identify effective leverage points for the optimization of multifunctional landscapes.

Providing robust projections: Finding optimal adaptation solutions for terrestrial and freshwater systems under climate change conditions, including weather extremes.

High-resolution climate model projections indicate that extreme weather events will occur more frequently. Summer droughts such as in Germany in 2018, for example, will be the rule rather than the exception and will affect terrestrial ecosystems, water bodies, and urban areas. Robust Earth system models are needed to draw realistic pictures of the future, including weather extremes, and hence enable detailed multi-sectoral (agricultural, forest, water systems, etc.) impact studies in collaboration with T5's Subtopics. We have unique know-how to deliver scalable, mechanistic, adapted complexity, robust, and transferable (SMART) model systems of unprecedented time and space resolution. These model systems are parameterized in a goal-oriented approach and deliver reliable future projections of impacts on terrestrial and freshwater systems together with a quantification of the overall result uncertainty. Due to this unique approach, various adaptation strategies, including planning for socio-economic sectors and policymaking, can be developed at a regional scale but with a consistent national and continental coverage. To parameterize these models we develop and apply innovative observation and monitoring strategies, using integrated observatories like TERENO at national scale or eLTER (Long-Term Ecosystem Research in Europe) at European scale, event monitoring like through MOSES as well as integrated products from our new Remote Sensing Centre (RSC). The most advanced computing and data science methods like exascale and quantum computing, as well as AI technologies, Open Science and technologically intelligent multi-thematic data repositories do significantly support the progress.

Making multifunctional landscapes and resilient cities: Developing governance mechanisms, policy options, management strategies, and picturing transformation pathways that reconcile societal demands and the integrity of the environment.

Balancing resource use and the multitude of landscape functions (e.g., air and water quality, soil carbon, nutrient cycling, biodiversity, pollination, contributions to human health) requires an understanding of societal and economic drivers, behavioral responses, governance structures, and societal change processes. To this end, the full range of social sciences (economics, sociology, political science, law, and systems analysis) will be deployed, and results of biodiversity and water research from the natural sciences will be integrated. Based on this, appropriate transformation pathways towards multifunctional landscapes will be developed and assessed. Stakeholders will be involved in science-policy-dialogues to ensure coherence, compliance, legitimacy, and effectiveness of policy recommendations in complex decision-making arenas. Based on our long-lasting experience in inter- and transdisciplinary research we derive policy options for, e.g., the EU Common Agricultural Policy, or the definition of water quality targets for the EU Water Framework Directive beyond 2027. Cities are decision-making arenas of special interest: being hot spots of increasing land and resource use, greenhouse gas emissions, and a multitude of diverse actor groups, they specifically require a societal balancing of diverse interests and multiple trade-offs. The urban-rural nexus opens up options for sustainable transformation pathways, for example, in the fields of green and blue urban infrastructures.

Strategic guidelines (FoPoZ). T5 brings together comprehensive process understanding for ecosystems and landscapes in order to improve the ability to forecast the impacts of global and climate change, particularly at the regional level, and to develop new concepts for the use and sustainable management of multifunctional landscapes. T5 provides: i) approaches to reconcile water security and ecosystem services with the functions and limitations of their natural contexts, e.g., in agriculture, ii) adaptation measures to current climate dynamics including extreme events like floods, droughts, and heat, iii) transformation pathways towards livable urban areas in order to increase the resilience and quality of life in the face of climate change and increasing extreme events. iv) The LandTrans simulator as a tool for analysis, forecasting, and knowledge synthesis will expand the transfer of knowledge to science and society.

Function and contribution of the Topic within the Program. T5 generates knowledge-based recommendations for multifunctional terrestrial landscapes. It opens avenues for inter- and transdisciplinary research by applying an extended synthesis approach that integrates individual compartments, socio-economic sectors, different spatial and temporal scales, and stakeholder knowledge. T5's modeling strategies reveal new paths for analyzing and modeling impact chains of global and climate change. With the inclusion of social sciences, T5 will contribute to the overall Program's mission to derive target-oriented and actionable knowledge for decision-makers, stakeholders, and the general public. It will be instrumental for HI-CAM and SynCom.

Close links exist to T2 in the field of permafrost. Jointly with T4 transitions between the terrestrial and the coastal areas are addressed, e.g., water bodies being analyzed from their sources to the sea, or coastal urban areas; a land-based toolkit will be developed, adding modules for science-practice interfaces and tailored products for end users. Jointly with the marine biodiversity expertise in T4 and T6, T5 will shape biodiversity research in the national and international research community. For T7, T5 provides spatially-explicit renewable energy and biomass scenarios and assessments, and thus complements T8's georesources-based work towards the Energy Transition. As chemical pollutants are considered in T5's water-related research, there are close links to T9 and CARF MACE.

Highlights. **Cross-compartmental and cross-sectoral approach**. T5 particularly focuses on the interdependencies and relationships between different environmental compartments, socio-economic sectors, and regional and temporal time scales, e.g., when analyzing pollutants in agro-environmental systems or climate impacts and adaptation strategies. **Chain of knowledge creation:** A broad range of social-sciences disciplines and proven collaborations between social and natural scientists enables T5 to be effective over the entire chain of knowledge creation: from detailed process-based system knowledge (e.g., understanding the natural dynamics that limit the stability of the Earth surface system and its ability to yield resources), over target knowledge (e.g., defining thresholds and critical values), up to the desirable actionable knowledge (effective policy strategies for pathways towards multifunctional landscapes). By doing so, it strongly adds to transfer activities and advances the synthesis outcomes of the entire Program. **SMART modeling**: Most global change models address environmental problems on regional scales with low resolution, while process-based models normally focus on small scales that are not transferable. T5 will deliver models that are robust, based on process understanding resulting from in situ observations and experiments, and at the same time offer high predictive and transferable power. **Understanding adaptation to past and present climate changes**: By combining research on past and present pristine terrestrial surface systems and anthropogenic landscapes, T5 will robustly distinguish human impacts from changes inherent to Earth's natural system behavior. **Integrative biodiversity and ecosystem research**: Based on its outstanding performance in terrestrial biodiversity and ecosystem research, as part of the German National Centre for Integrative Biodiversity Research (iDiv), and in close relationship with complementary approaches on coastal and marine systems of T4 and T6 including the newly formed HIFMB, T5 conducts research on species community assembly rules and novel ecosystems. Together with T4 and T6, the Topic builds a hub of biodiversity and ecosystem research within the Program.

B) Main research and structural objectives

Research Objectives.

- **Objective 1:** Project the functioning and provisioning of future terrestrial ecosystems based on the understanding of how multiple processes interact and how they scale up to heterogeneous landscapes under current and future conditions.
- **Objective 2:** Identify leverage points for achieving sustainable management of future terrestrial ecosystems and biodiversity by connecting natural and socio-economic factors to provide policy-relevant knowledge on how to develop landscapes that reconcile human appropriation of natural resources, halt and reverse biodiversity loss and soil degradation, and promote sustainable ecosystem functions and services.
- **Objective 3:** Foster and implement a new generation of system analyses for the entire water cycle that link hydrology, biogeochemistry, and aquatic ecology, at scales from local 'hot spots' through entire catchments to the continental scale as a prerequisite to reconcile water security for humans, food production, and aquatic ecosystems.
- **Objective 4:** Develop innovative integrated monitoring, assessment tools, and concepts for water accounting, water quality, ecosystem functionality, and risk management of hydrological extremes that support the identification of the most effective governance and management options.
- **Objective 5:** Bolster anticipative understanding of the consequences of ongoing climate change by determining the impact of climate on natural terrestrial systems across time scales from deep geological time to the present day, with a focus on past warm periods and rapid climate change in the Quaternary.
- **Objective 6:** Constrain the mechanisms and interactions of key erosional and biogeochemical processes and fluxes at the Earth's surface, and determine how they affect life and climate by shaping topography and transferring nutrients and atmospheric trace gases.
- **Objective 7:** Characterize the past, present and future transition of northern permafrost ecosystems under a warming climate and changing land use, and constrain related global and regional feedbacks.
- **Objective 8:** Develop and implement model concepts hand in hand with Earth observation and big data analysis to observe, analyze and model terrestrial systems on regional scales following the underlying paradigm of scalability, robustness, and transferability.
- **Objective 9:** Develop and apply a new generation of models that are able to predict impacts of regional extreme events to a formerly unknown extent of precision and that allow the development of optimal adaptation strategies.

- **Objective 10:** Understand human and societal drivers, causes, and impacts (including conflicts, synergies, trade-offs, rebound effects, and paradoxes) of societal responses to global change and extreme climate events.
- **Objective 11:** Develop governance mechanisms, policy options, and management strategies to secure environmental resources under global change and enhance transformations towards multifunctional landscapes, including urban spaces and the urban-rural nexus.
- **Objective 12:** Synthesize results into a Modular Simulator of Transitions for sustainable multifunctional landscapes of the future (LandTrans) with the aim to make knowledge accessible to stakeholders, decision-makers, and the general public (input to SynCom).

Structural Objectives.

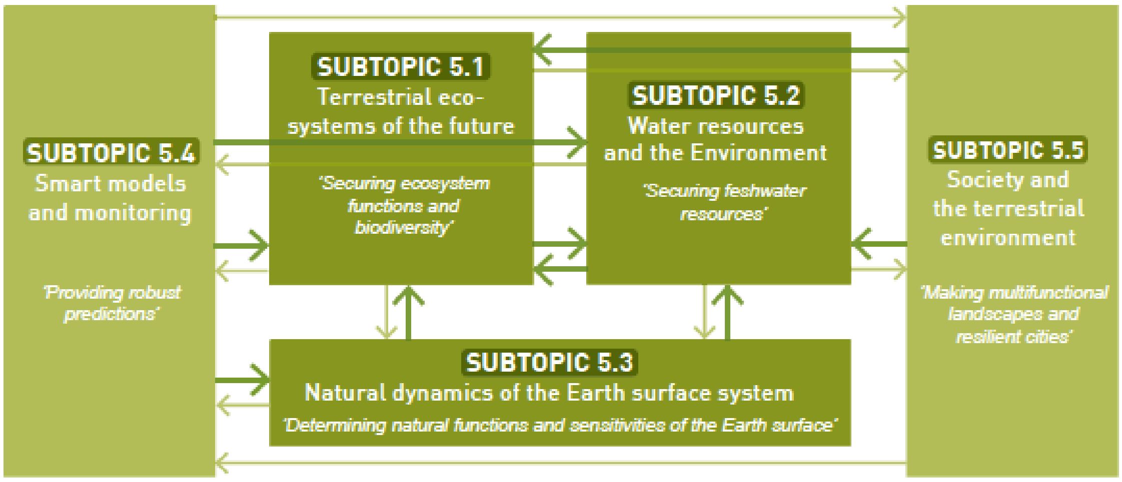
- ESFRI eLTER RI: Develop an integrated European Long-Term Ecosystem, Critical Zone & Socio-Ecological Research Infrastructure in collaboration with the TERENO partners in the Helmholtz RF E&E and 19 European countries. The overall systemic approach of this infrastructure will allow T5 to monitor and analyze temporal variations and long-term trends across disciplines and across multiple scales.

C) Structure of the Topic and motivation of Subtopics

Introduction of Subtopics. To reveal and map impact chains cutting through the whole terrestrial system, T5 follows a modular set-up: Land use – with a special focus on ecosystems, biodiversity, and soils – is addressed in ST5.1, and inland waters – including extreme events – in ST5.2. ST5.3 explores climate change interactions from geological times to the present as a backdrop to human interventions and analyzes the interfaces between the Earth surface system and the geo- and atmosphere. Data, monitoring, and modeling strategies converge in ST5.4. Socio-economic drivers and societal problem-solving concentrate in ST5.5.

Contributions of the Centers to the Topic. T5 is built around the complementary perspectives, approaches, methods, and results of four Helmholtz centers to exploit synergies and tackle scientific challenges of common interest. **UFZ** brings competences in ecosystem- and water-related research, regional model-based predictions/projections, and social sciences. **GFZ** contributes competences in Geosciences, Earth observation, and hydrological extremes. **AWI** adds permafrost research and polar terrestrial ecology, and **HZG/GERICS** supplies expertise in regional climate modeling and climate service development, especially with regard to tool boxes for urban spaces.

TOPIC 5 | Landscapes of the Future: Securing Terrestrial Ecosystems and Freshwater Resources under Natural Dynamics and Global Change



Integrated approaches for pathways towards multifunctional landscapes, resilient cities and the urban-rural nexus
Biodiversity • ecosystems services • freshwater • extreme climate events • natural and human impacts and trade-offs
SMART model systems • multi-thematic data repositories • policy options for complex decision-making arenas

Important Topic links:
- TOPIC 1: GHG fluxes in complex landscapes
- TOPIC 2: Permafrost and paleoclimate
- TOPIC 3: Changes in the terrestrial surface
- TOPIC 4: Solute fluxes, modeling
- TOPIC 6: Biodiversity
- TOPIC 7: Biomass scenarios, life-cycle assessments
- TOPIC 8: Bioenergy and renewables
- TOPIC 9: Fate of micropollutants

Selected Cross-Cutting Activities:
- HI-CAM: Pictures-of-the-Future approach
- REKLIM: Regional climate strategies
- TERENO: Water quality & storage, biodiversity
- MOSES: Source-to-sink, model coupling
- Remote Sensing: Land use, infrastructures
- BioEco meets Energy: Spatially-explicit scenarios
- Resilient Urban Spaces: Infrastructures, governance
- MACE: Social factors, chemicals in water
- ESM, Digital Earth: Models and monitoring

External key partners beyond universities:
- National: iDiv, DBFZ, ZALF, DLR, PIK
- European: CEH (UK), SYKE (FIN), JRC, Stockholm Resilience Center (SE)
- International: SESYNC, NCAR, Global Institute for Water Security, NASA (US)
- Networks: BonaRes, PEER, eLTER, EnMAP, ECMWF, GRACE and GRACE Follow-on
- Transfer: UBA, BfN, EEA, UNEP, IPCC, IPBES

Fig. 5.1: Graphical scheme of Topic 5: An integrated approach to multifunctional landscapes, resilient cities, and the urban-rural nexus.

D) Subtopics

Subtopic 5.1 Terrestrial ecosystems of the future

Stefan Klotz, UFZ

Scope and challenges. Humanity depends on stable and fully functioning ecosystems. At the same time, human activities form the biggest threat to ecosystems, manifested in the loss of biodiversity and in forest and soil degradation, with climate change representing an increasing pressure. The major challenge of the coming decades is to develop solutions to ensure that future ecosystems are resilient and fulfill basic societal needs. Our research aims at halting ecosystem degradation while simultaneously maintaining the provisioning of natural resources. Answers to this challenge lay in the sustainable development of landscapes in rural and urban areas – goals that are voiced, inter alia, in the German Biodiversity Strategy and in the SDGs. We are among the few research groups worldwide that have the capabilities to provide synthesis knowledge for solutions by combining various techniques, such as experimental approaches (including the development and use of innovative technologies), long-term observations, distributed studies in regional and global networks, as well as scenarios, simulation, and modeling.

Main objectives.

- Derive a systemic understanding of complex interactions and feedbacks, including community assembly rules and biotic-abiotic interrelations that buffer soils, biodiversity, and ecosystems against global change across a range of spatio-temporal scales (in cooperation with T6 and T7).
- Develop scenarios on possible futures using combinations of theory and modeling based on experimentation and observations as a basis to derive policy options and management strategies.
- Identify leverage points for achieving sustainable management of future ecosystems and landscapes by integrating natural and socio-economic variables in model regions.
- Provide policy relevant knowledge on how to develop landscapes that reconcile human appropriation of natural resources, halt and reverse biodiversity loss and soil degradation, and promote sustainable ecosystem functions and services.

Work program. We aim to develop effective solutions for ensuring long-term sustainable human well-being while protecting the natural world that we depend on. This requires process-based understanding in order to provide projections across the range of scenarios that depend on climate projections and alternative socio-economic responses. Building on our competencies, we will employ a range of approaches from process-based theory and models, ecological data and informatics, experimental platforms, and sensor technologies as well as field observations. We will use existing and novel monitoring techniques, which provide the data for **Essential Ecosystem Variables (EEV)** for **quantifying states and trends in ecosystems and their functions** in differently managed landscapes. This will expand the current framework of Essential Variables developed for biodiversity and climate, which focuses on organisms, temperature, and precipitation but ignores other abiotic components (e.g., energy, matter, and water cycles) and socio-ecological feedbacks that are fundamental

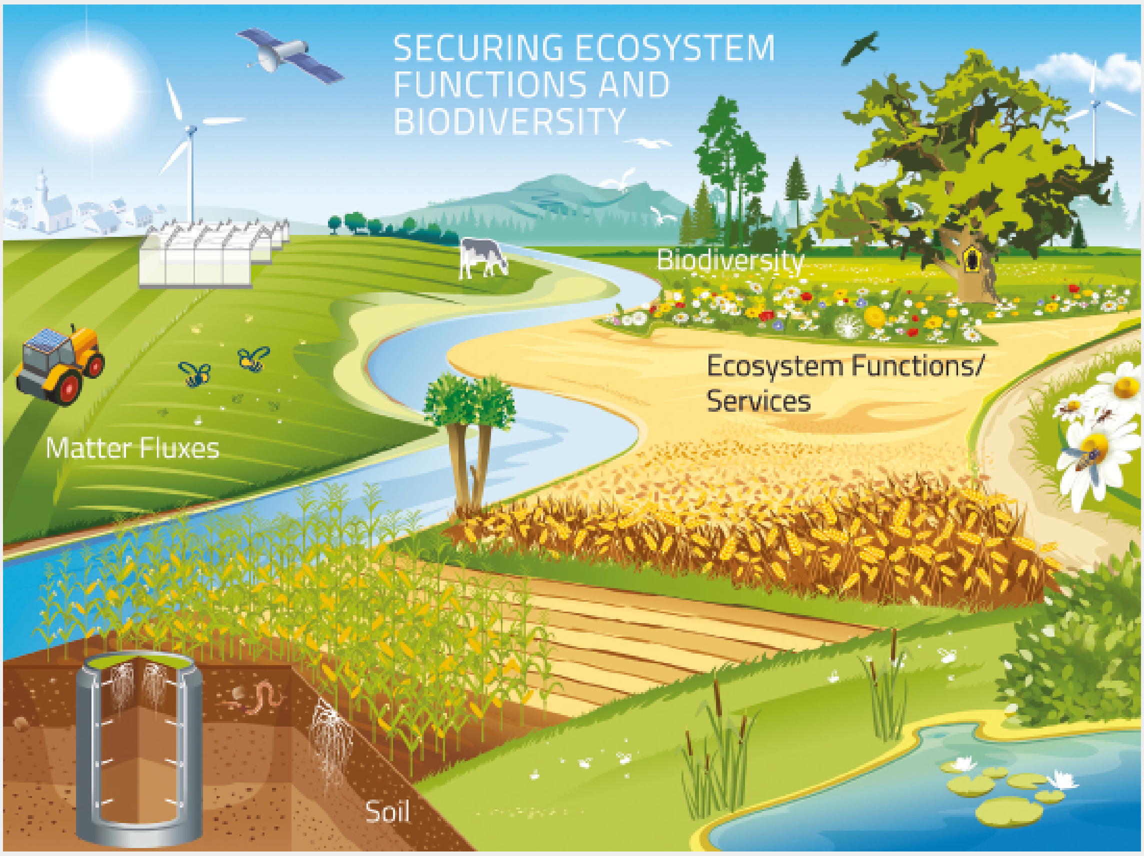


Fig. 5.2: Securing ecosystem functions and biodiversity. ST5.1 analyzes multiple interactions between abiotic and biotic processes (including above and below ground), and land use impacts at different organizational levels (from molecules, genes – physiology – species, populations – communities – to ecosystems) and across spatio-temporal scales. ST5.1 will provide a deeper understanding of the functioning and the dynamics of terrestrial ecosystems under the conditions of global change. We will provide visions, scenarios, and models for securing biodiversity, ecosystems, their functions, and services.

to ecosystems. Based on tested EEV and models applied to specific landscapes in Germany, we will provide essential data to simulate managed landscapes under transition as well as to develop possible pathways of managed landscapes that secure ecosystem functions, soils and biodiversity. UFZ's outstanding experimental platforms (mentioned below) further allow us to test the dynamics and sensitivities of ecosystems to regionally relevant global change perturbations, needed for meaningful projections. Our focus will be on ecosystem services from terrestrial landscapes critical to sustaining human well-being, including provisioning services, soil carbon and nutrient cycling, water quality, and biodiversity (e.g., pollination). Solutions for a sustainable management of future ecosystems and biodiversity require that the processes underlying ecosystem functions and services are understood, as well as the consequences of human behavior. We will build on well-established partnerships with socio-economic experts (ST5.5). Identifying leverage points for management and policy options requires identifying the ecological consequences of alternative future ecosystems and landscapes that result from the projected effects of multiple global change drivers and our adaptive responses.

Understanding processes and related functions, interactions, and feedbacks. We will synthesize theories that provide mechanistic representations of changes and consequences in ecosystems. Building on our existing integrative approaches, linking synthesis, theory, and modeling will put us in a unique position to identify potential **novel ecosystem states** arising from the combined effects of multiple global change drivers (e.g., climate, land use, non-native species, etc.) and being implemented as scenario projections. This integrative theory and modeling approach relies on observational and experimental data and the excellence of UFZ collaborative infrastructures.

We will be able to identify German model regions (based on eLTER, TERENO, MOSES) to establish science-policy-stakeholder interfaces that support the transition of agriculture technologies and the implementation of more environmentally-friendly methods, and where **long-term observations and experiments** that support terrestrial and aquatic biodiversity monitoring in Germany will be carried out. We will expand these activities to the newly developed European scale monitoring network eLTER, which was recently listed on the Roadmap of the European Strategy Forum of Research Infrastructures (ESFRI). This will allow effective monitoring of temporal variations and long-term trends of biodiversity loss (cf. 'insect decline' – addressing the strategic guidelines of BMBF), including taxonomic, phylogenetic, genetic and functional aspects, as well as inter-kingdom interactions (e.g., pollination) related to land use and climate change, and provide data for modeling and projecting managed landscapes of the future.

Based on the most recently available remote sensing data, we will develop spatial high-resolution soil information at a national scale (Germany, cooperation with DLR) as a basis for a first national assessment of soil functions. This will be based on soil attributes that are suitable indicators for the various soil functions including productivity, C/N cycling (ST5.3), water storage and filtering (ST5.2) to deduce **'Essential Soil Variables'** (ESV) with high-resolution (fields) at large spatial extent (national and beyond). While in the past ESV mostly consisted of physical and chemical parameters (e.g., carbon and nitrogen), recent advances in molecular techniques make it possible to tackle biodiversity in soils at all scales. Developing and integrating ESV enables us to identify and quantify soil functions more specifically, and to define indicators for assessing soil ecosystem functions and services. The generated systemic understanding of physical, chemical, and biological processes in soil will allow for projecting the impact of land use and global change on soil functions based on a systemic model approach. Using this knowledge, we will develop **steering mechanisms for buffering soil processes and functions** against external perturbations.

Identify leverage points for management and policy options. Previously unknown landscape-scale feedbacks and highly uncertain processes (e.g., the interplay of land use intensity with different aspects of biodiversity and ecosystem functions and services in multi-trophic feedbacks, such as biocontrol, herbivory) will be specified and coded in modular models, which can be incorporated in larger simulation and modeling initiatives. This new synthesis of knowledge, which requires various techniques (e.g., experimental approaches to actually detect complex process interactions and to identify key system variables) in addition to modeling, data science and big data analysis (ST5.4), will substantially increase our capacity to **quantify the interaction of land use change** with biodiversity and ecosystem functions/services, such as soil fertility or water availability (according to the recommendations of the recent IPBES and IPCC special reports) along gradients of land use composition, configuration, and intensity. The results will be incorporated into scenarios of selected elements of biodiversity accounting for dispersal dynamics, trait diversity and species interactions, policy options, and management strategies for recent and novel ecosystems, including soil systems. Novel scenarios, i.e., land use change pathways, are developed in cooperation with social scientists and by applying model-based back-casting approaches, which are novel through the incorporation of the inherent but widely ignored biodiversity-production feedback. They provide knowledge about how to induce changes in farmland management with regionally adapted solutions, reconciling human appropriation of natural resources and biodiversity preservation. Using this technique, we aim at identifying leverage points such as consumption or dietary changes, subsidies, or certification schemes that support transitioning from conventional farmland management to landscape multifunctionality, with the goal to reach resilient landscapes for biodiversity and people. This synthesis of natural as well as social science knowledge will be used to identify the best possible instruments that support balancing agricultural production, soil systems, terrestrial water bodies and biodiversity, quantified and specified in novel scenarios.

Our systemic understanding and the new generation of ecosystem models will enable projecting relationships under non-analogous conditions to transfer knowledge and model concepts to different geographic regions, which relate to different climatic situations (as studies in the Global Change Experimental Facility – GCEF) or even different socio-economic contexts (such as various case studies for instance in EU projects like BESTMAP). A common result of synthesis work will be a modular simulator for agricultural landscapes under transition (LandTrans AGRI) which studies ecosystems dynamics in response to climate change and human activities (c.f. M5.13-3 (2025) in ST5.4 jointly with ST5.2 and ST5.5).

Given that the newly developed concepts and models are explicitly tailored for applications in non-analogous conditions, we investigate transferability in a wider geographic range and other world regions to identify option spaces that reconcile provisioning services (e.g., food, bioenergy) and biodiversity protection. We envision to implement research projects in hot spot world regions that request support for boosting yields (such as sub-Saharan Africa, Asia) but also maintain biodiversity hot spots (such as Brazil, Mexico, etc.). We aim at a diverse global network in which solutions to the sustainable development of land management is implemented (for instance throughout existing GIZ collaborations), which underpins our global scale science-policy support in assessments by IPBES and IPCC.

Deliverables (D) and Milestones (M)

- **D5.1 (2024):** Conceptual model of EEV and ESV, capable of dealing with unknown state of the ecosystems. **M5.1-1 (2022):** Identification of potential novel ecosystem states.
- **D5.2 (2025):** Modular simulator for agricultural landscapes under transition (LandTrans AGRI). **M5.2-1 (2024):** Indicators for assessing soil ecosystem functions and services defined. **M5.2-2 (2024):** Interactions of land use change with biodiversity and ecosystem functions/services along gradients of land use structure and intensity identified.
- **D5.3 (2027):** Leverage points/German model regions. **M5.3-1 (2022):** German model regions for science policy stakeholder interfaces identified. **M5.3-2 (2026):** Knowledge and model concepts transferred to different geographic regions.
- **D5.4 (2026):** New scenarios/pictures of the future. **M5.4-1 (2024):** Interaction of land use change with biodiversity and ecosystem functions/services along gradients of land use structure and intensity quantified.

Infrastructures and specific resources. The Experimental Research Station Bad Lauchstädt, an international hub for ecological experiments, allows multi-scale experimental investigations of different ecological systems. The experiments are incorporated in several global networks (e.g., Drought-Net, Nutrient-Network) to analyze the effects of droughts, multiple nutrients, and other land use and global change impacts on species communities and ecosystems. The Global Change Experimental Facility (GCEF) is a unique field experiment that facilitates the investigation of the effects of future climatic conditions on ecosystem processes under different land use scenarios. This long-term experiment started in 2014 and is planned to be conducted for at least 15 years to understand long-term trends of changes in agro-ecosystems.

Cooperation partners. iDiv is a primary strategic partner of ST5.1 as its expertise in biodiversity and ecosystem science complement each other. Key partners of our soil science research are 51 German institutions within the frame of the soil science network **BonaRes**, including **ZALF** (Leibniz Centre for Agricultural Landscape Research). For syntheses the collaboration with the syntheses center of the University of Maryland (**SESYNC**), **sDiv** (Synthesis Centre of iDiv) as well as the **University of Leeds**, the **Stockholm Resilience Centre** and the **Vrije Universiteit Amsterdam** are central. In addition to these partners, the **University of Helsinki** and the **Centre for Ecology & Hydrology (CEH)** are of importance, especially for the eLTER process.

Risks and Opportunities. Scaling processes to the landscape level and beyond may reveal gaps in process, biodiversity, and ecosystem understanding for different types of land use with climate and water as increasingly relevant pressures. These gaps will be filled by intensifying collaborations within and beyond our networks. We see an opportunity to be a hub in research of terrestrial ecosystem functions and biodiversity. These gaps will be filled by intensifying collaborations within and beyond our networks. We see an opportunity to be a hub in biodiversity research of terrestrial ecosystems. Expanding this strength to marine ecosystems appears as an ambitious challenge yet achievable jointly with T6. We strive to have a general strategy planning for environmental and nature protection in terrestrial and marine areas.

Subtopic 5.2 Water resources and the environment

Dietrich Borchardt, UFZ

Scope and challenges. Pressures and impacts on water quantity, water quality, and aquatic biodiversity already exceed safe boundaries in many regions of the world. Climate change, population growth, land use change, and agriculture are key drivers among the various factors causing the further increase of related risks. ST5.2 addresses the dynamic relationships of coupled human-natural systems and how they are ultimately threatened with regard to water security. The challenge will be to take into account all relevant natural and anthropogenic factors in a quantitative systems approach. This means to cover the essential natural and socio-economic system elements, at spatial scales from catchments over landscapes to continents, and at temporal scales from short-term events to multi-decadal trends (Fig. 5.3).

Main objectives.

- Develop a systems approach for understanding and determining the time-varying interactions of the atmosphere, catchments, and society that shape hydrological risks.
- Foster a new generation of system analyses that link hydrology, biogeochemistry, and aquatic ecology. Innovatively monitored across scales and modeled in LandTrans, we determine trajectories on how to achieve water security in coupled human-natural systems.
- Provide solutions for the management of changing land use, resilient urban development, and climate adaptation by consistent assessments of cause-effect-intervention chains.
- Develop and demonstrate innovative and practically relevant solutions for regional use cases in a network of national and international catchments.

Work program. ST5.2 has the unique opportunity to coherently **observe, explore, and analyze the various coupled compartments and critical controls of the entire water cycle in a quantitative systems approach**. Our synthesis of so far fragmented monitoring, experimental process identification, data-driven analyses, and explorative modeling will allow us to quantify water fluxes and storages in complex catchment settings. We will investigate which substances from natural and anthropogenic sources get into the water cycle through which pathways, as a foundation to understand how they are converted along flow routes from inland to coasts. As a complement to that understanding, we want to qualitatively and quantitatively determine safe boundaries for water security under given natural constraints and in multi-functional catchment configurations. ST5.2 focuses on identifying innovative hydro-ecological and cross-sectoral management approaches that take the entire water cycle into account, minimize water-related risks, and control direct loads (nutrient loads such as nitrates, phosphates, and carbon, or harmful substances such as micropollutants jointly with T9, input to MACE) as well as indirect loads and natural attenuation. In all these facets, socio-economic conditions (e.g., costs and benefits, legal frameworks, policy instruments, management options) play a substantial role for effective management (cf. ST5.5).

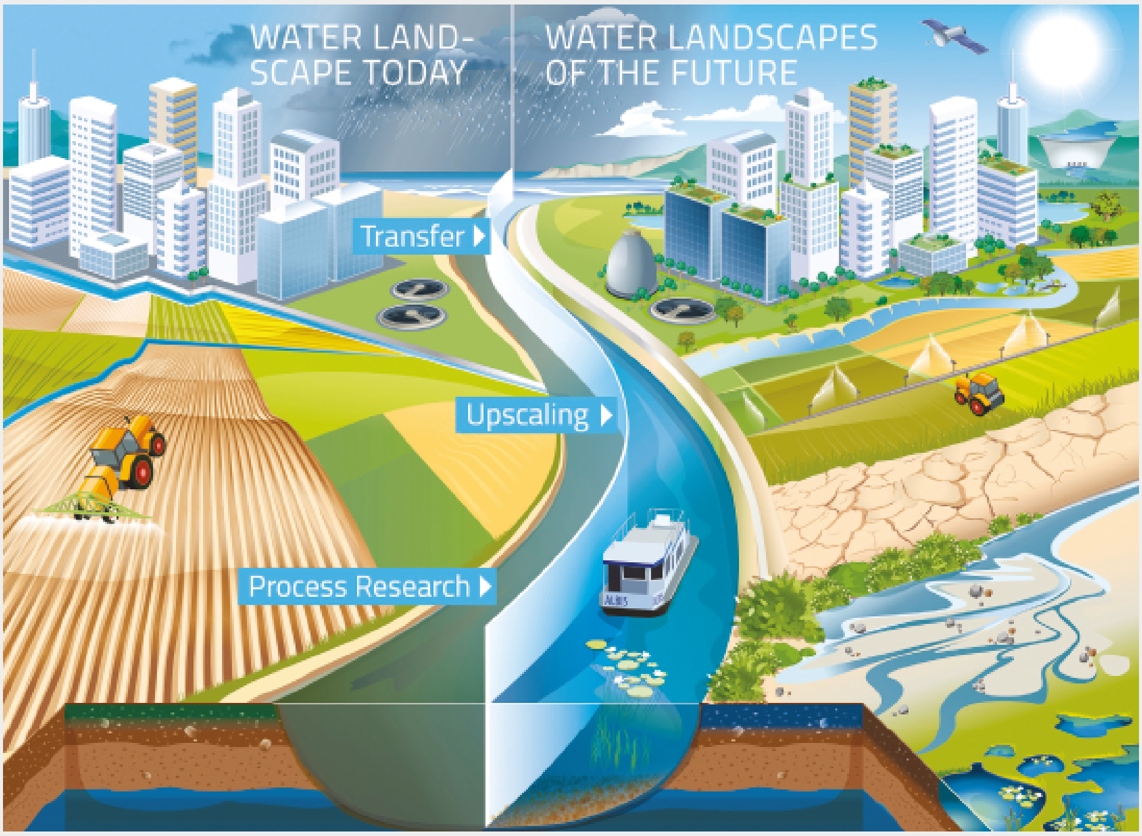


Fig. 5.3: Securing freshwater resources and aquatic ecosystems. ST5.2 analyzes dynamic interrelationships of climate change, population growth, and land use changes with societies, with the environment and how the latter ultimately are threatened with regard to water security.

For this purpose, ST5.2 will develop innovative concepts, methods, and models to be incorporated in LandTrans and enable the causal analysis of interlinked natural and human elements of the water cycle across wide ranges of spatial and temporal scales. With this tool set, ST5.2 will determine trajectories towards future water landscapes that secure water resources for human needs and healthy aquatic ecosystems in a balanced way for a wide range of socio-economic settings.

A pillar of our research will be the **analysis of hydrological processes, states, and changes from plot scales, over catchments to continental and global scales.** We will integrate networks of hydrological monitoring sites, mobile monitoring systems, satellite observations, and large-scale modeling jointly with ST5.4.

Innovations comprise **assessing water storage changes by ground-based and satellite gravimetry.** GRACE follow-on missions (GRACE-FO) of satellite gravimetry will provide sufficiently long time series to assess long-term variations and trends of the water cycle with increasing resolution, quantify and consistently close the water balance, and determine its space-time variability. We will establish terrestrial gravimetry as a novel hydrological sensor system, understanding the specific expression of climate change in hydrology and subsequent processes. The combination of these monitoring techniques will put us in a position to develop comprehensive indicators of extreme hydrological events based on total landscape wetness at the regional scale. These analyses will be complemented by isotope-based monitoring of dynamic travel time distributions and their process-based modeling at large scales. We will implement a regional flood model chain to quantify interactions and change in flood risk systems in order to assess climate adaptation strategies and provide worst-case scenarios and risk statements for flooding in Germany linked with T1.

Deciphering the hydrological, geochemical and biological key processes that are controlling catchment-scale water budgets, solute transport and ecosystem internal controls puts us in the forefront to deploy and further develop complexity-reduced water and mass flux models. These will have a strong mechanistic basis and work reliably for analyses of global change impacts. In particular, this research provides the fundaments for the process-based modeling in the aquatic modules of the T5 synthesis product LandTrans jointly with ST5.4. These modeling tools will allow us to study and quantitatively assess ecosystems' dynamics in response to climate change and human activities using consistent scenarios together with ST5.1 and ST5.5. The ultimate goal will be to deliver reliable projections for trajectories on how to simultaneously achieve a water-secure human consumption, food production, and protection of the aquatic ecosystems.

With regard to solute fluxes and water quality, we will focus on the **characterization of source-configuration, hydrologic connectivity, and dynamic travel times in entire catchments** as first-order controls of solute export dynamics. We are aiming to identify and model hydro-biogeochemical proxies for solute transport for entire river networks employing novel approaches based on in situ high-frequency measurements and high-resolution analytics. This advancement opens up the opportunity to estimate solute uptake and mineralization as ecological key functions of natural attenuation across system compartments, from water body to catchment scale and extending to coastal zones together with T4. This will allow us, together with ST5.1 and ST5.3, to estimate the role of aquatic ecosystems in the regional to global processing of key elements (i.e. carbon, nutrients) and to assess the human alteration of these essential matter fluxes.

Aquatic ecosystems experience rapid modifications which challenge present status-based approaches in ecosystem assessment and management. We will focus on an alternative approach and **decipher the effects of human-made pressures on biodiversity and interlinked ecosystem functions, including their mutual relationships.** Linked with ST5.1 and T9, we aim to bridge ecotoxicology and aquatic ecology by quantifying multiple stressors and their effects across ecological organization levels. With new function-based indicator sets, we will provide a reliable science base to manage multiple stressors in aquatic ecosystems.

Based on our broad expertise and our networks on integrated water research we are aiming to establish a **leading hub for tackling and solving complex water issues** at national, European and global scales with showcases demonstrating cutting-edge science-based solution options.

Deliverables (D) and Milestones (M)

- **D5.5 (2026):** Assessments, indicators of space-time variability of the water balance, and hydrological extremes. **M5.5-1 (2024):** Terrestrial gravimetry as a novel hydrological sensor system. **M5.5-2 (2024):** Regional flood model chain.
- **D5.6 (2026):** Complexity-reduced water and mass flux models with a strong mechanistic basis. **M5.6-1 (2022):** Identification and testing of proxies. **M5.6-2 (2022):** Spatially explicit and dynamic modeling across scales. **M5.6-3 (2024):** Novel assessments of natural constraints versus human impacts on water quantity and quality.
- **D5.7 (2026):** Deciphering natural and anthropogenic pressures on aquatic biodiversity and interlinked ecosystem functions. **M5.7-1 (2022):** Development and testing of function-based indicator sets. **M5.7-2 (2024):** Novel indicator-based assessments of multi-functionality and aquatic ecosystem health.

Infrastructures and specific resources. A backbone for the research in ST5.2 is the TERENO hydrological observatory site Central Germany (Bode catchment). Jointly with ST5.1 it will be part of the eLTER RI and focus on long-term observation of structures, functions, and biodiversity in a network of terrestrial and aquatic ecosystems across Europe. The TERENO Northeastern German Lowland Observatory provides an essential site for T5 for a number of research challenges, such as understanding feedbacks between climate, vegetation and subsurface water storage, groundwater-surface water interactions, and greenhouse gas budgets across anthropogenic impact gradients.

The CTA MOSES comprises modular, highly flexible and mobile observation systems for the observation of catchment-wide fluxes of energy, water, and nutrients triggered by extreme hydrological events including inland to coastal linkages (link to T4). An initial focus will be on the Elbe catchment with the perspective to be transferable for other regions in Europe and globally.

MOBICOS riverine mesocosms are unique mobile laboratories to mechanistically study ecological responses along natural and anthropogenic impact gradients. The research vessel ALBIS, which has been specially designed and equipped for conducting research on large rivers including shallow waters, and the laser-scanning microscopy are particularly useful to conduct research on hydrological and biogeochemical cause-effect chains and feedbacks.

The GRACE-FO satellite mission, implemented by NASA and GFZ and successfully launched in May 2018, continues the 15+ years' legacy of GRACE, tracking Earth's water movement and surface mass changes across the planet. The resolution strived for is regional, i.e., an order of magnitude 10,000 km^2, and from monthly in time for long-term assessments down to daily resolution for near-real-time applications related to extreme events. Another essential infrastructure for ST5.2 is ZUGOG (Zugspitze Geodynamic Observatory Germany), operated by GFZ, as part of a global network of currently 40 observatories with superconducting gravimetry. It allows us to study water storage variations in one of Germany's most vulnerable areas, including glaciers and mountain permafrost, to climate change.

Cooperation partners. Technical University Dresden (TUD) as one of the leading technical universities in Germany is connected with UFZ as a strategic partner. Complementary expertise comprises urban systems, molecular limnology, environmental monitoring, and geo-information techniques. Important national cooperation in the field of water and pollutants has been evolving since 2010 with the universities of Tübingen, Stuttgart, and Hohenheim. A competence cluster on Water and Earth System Science (WESS) was founded to investigate the dynamics of pollutant fluxes in the landscape and their interconnections with the atmosphere, the soil, and the groundwater.

Internationally, the University of Florida (UF) and Purdue University (PU) are key strategic partners. The cooperating groups at UF focus on water resources, aquatic ecosystem health, and minimizing human impacts on natural systems. Purdue University (USA) integrates engineering and science concepts to solve major environmental problems using an ecological approach.

With regard to science-policy-interfaces, UFZ has established multi-faceted cooperation with the German Federal Environment Agency (UBA) on science advances for implementing national and European environmental legislation and for developing a long-term water strategy for Germany. GFZ cooperates with the Federal Office of Civil Protection and Disaster Assistance (BBK) on extremes, and with the Federal Agency on Cartography and Geodesy (BKG) on gravimetric monitoring. Since January 2014, UFZ has led the European Topic Centre on Inland, Coastal, and Marine waters (ETC-ICM). ETC-ICM establishes a seamless environmental information system to assist the EU Commission, the European Environmental Agency (EEA), and EU member countries in their attempts to improve the aquatic environment. UFZ together with the United Nations Environment Programme (UN-Environment, former UNEP) initiated a World Water Quality Alliance in 2018 mandated by the United Nations Environmental Assembly in 2017 with the objective to develop a comprehensive global water quality assessment until 2025.

Since 2002 GFZ has been a partner in the joint US-German GRACE/GRACE-FO Science Data System, together with the Jet Propulsion Laboratory in Pasadena and the University of Texas Center for Space Research in Austin, and leads the European GRACE/GRACE-FO Science Team.

Risks and Opportunities. Deciphering the hydrological, geochemical, and biological key processes that are controlling catchment-scale water budgets, solute transport, and ecosystem internal controls may reveal gaps in process identification and system-scale analysis. A particular risk for pan-European and global upscaling are the potential data, monitoring, and information gaps. These gaps will be addressed by intensifying collaborations with ST5.4 and expanding cooperation beyond our existing networks. The opportunity will be to put us in the forefront to deploy and further develop complexity-reduced water, mass flux, and hydro-ecological models with a strong mechanistic basis, which are still tractable at large scales and allow robust projections under data and information scarcity.

Subtopic 5.3 Natural dynamics of the terrestrial Earth surface system

Niels Hovius, GFZ

Scope and challenges. As the effects of rapid, ongoing global and climate change and the exploitation of Earth's landscapes, habitats and biota become ever more palpable, there is an urgent need to separate the underlying natural mechanisms from any processes originating in human activity. In this context, we ask "how do processes connecting the geosphere, atmosphere, and biosphere determine the natural dynamic of the Earth's terrestrial surface system, and which are the principal limits to the stability of this system?" We

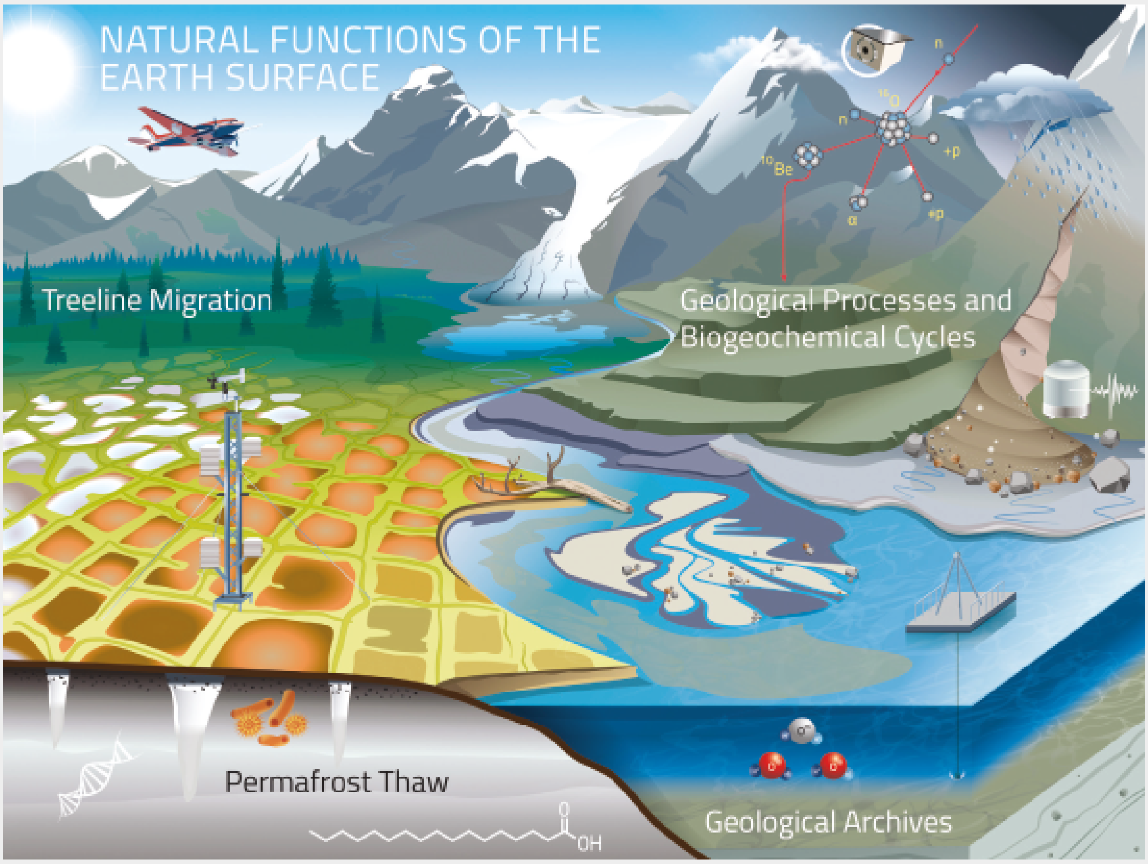


Fig. 5.4: ST5.3 will explore and constrain the natural mechanisms of links and feedbacks between climate, tectonics, landscapes, and biota, with a strong emphasis on the sensitivity of terrestrial surface systems to climate change. It will combine both monitoring and modeling of Earth surface processes and climate interactions on time scales from process events to major secular and cyclic trends (e.g., glacial cycles), and reconstruction of past processes recorded in deep time archives. This will help anticipate the impacts of future global and climate change. ST3 will work in sensitive systems globally, for example, in Arctic regions undergoing permafrost thaw.

pursue this question combining geodetic, geological, airborne and space-borne remote sensing, hydrological, geomorphological, geochemical, (paleo-)genetic, geomicrobiological, and process-based modeling methods. Combining work on modern systems with reconstructions from terrestrial archives, we resolve integral system behavior across all time scales of climate and environmental change, with a focus on essential process links, system perturbations and transients, highly-resolved natural archives and sensitive environments, including permafrost, wetlands and drylands, tectonically active terrain, and finely poised fluvial systems

Main objectives.

- Determine how the external influences of atmospheric and geological processes are expressed in topography, erosion, weathering and microbial traits and how we can invert these measurables for information about past conditions of the Earth system.
- Document and quantify Earth surface dynamics in geologically recent warm periods and past episodes of rapid climate change, with a focus on the Quaternary.
- Elucidate the links between Solid Earth dynamics, erosion, chemical weathering, and microbial activity, and determine how they affect the distribution of microbial life and fluxes of sediment, carbon, nutrients, and trace gases in the Earth's surface system.
- Understand thaw-driven landscape dynamics and impacts on biogeochemical cycling in permafrost regions.
- Characterize high latitude biodiversity change during warming and permafrost degradation on annual to orbital time scales and identify its consequences for ecosystem services.

Achieving these objectives will yield i) non-ambiguous estimates of the 'natural' state of key Earth surface system components and their variability, and of the time scales over which they change, ii) quantitative understanding of the biogeochemical processes that regulate Earth's climate, and iii) an ability to forecast trajectories of rapid environmental change in sensitive systems, exposed to the extremes of ongoing climate change. This all feeds into the overall Topic and contributes to the definition of anthropogenic impacts.

Work program. To determine how **external forcing by climate and geological processes is expressed in topography, erosion, weathering and microbial traits**, and to enhance our ability to invert these measurables for information about past forcing, we will develop novel techniques and models, and exploit strong spatial gradients in forcing, and exceptional geological archives. We will develop new methods (D5.3.1) to constrain terrestrial surface attributes and process rates, microbial biomarker proxies for climate assessment, geochemical tracers of fluid infiltration, and isotopic tools for quantification of weathering and erosion; methods for monitoring Earth surface composition from optical and hyperspectral data (EnMAP, PRISMA); methods for obtaining seismological and fiberoptic constraints on surface processes and properties; and high-resolution mass spectrometry and proxies in organic and isotope geochemistry, including pyrolytic H/C elemental parameters, plant and microbial biomarkers, FT-ICR-MS organic compound classification, stable metal isotopes, and cosmogenic radionuclide applications. Several of these techniques will have significant applications in other Topics (T2, T3, T4, T8). Time-series observations of Earth surface state and processes will be obtained in sensitive environments. To this end, multisensor networks for high-resolution monitoring of Earth surface processes and process cascades will be used to yield mechanistic insight and calibrated functions linking climatic and tectonic drivers and Earth surface process response. Satellite monitoring of land surface composition will track soil resources under changing climate and land use. Further, predictive landscape evolution models will give insight into how interactions of climate, tectonics, surface processes, and biota are recorded in topography and stratigraphy. To enable this, we shall develop mechanistic laws and numerical models for bedrock and glacial landscapes; use coupled records of past climate, tectonic, vegetation, biodiversity and landscape change to test dynamic processes included in climate models and isolate impacts of individual drivers; and implement optimally parameterized and computationally efficient Earth surface process models, designed together with ST5.4. Finally, we will deliver a quantitative understanding of the functional biodiversity in initial and extreme surface environments, supported by a catalog of strain collections of microorganisms, and microbial community inventories for systems impacted by tectonic and climatic perturbations.

Conditions substantially warmer than present have prevailed at times in the recent geological past, including MIS11 and MIS5. To probe Earth surface dynamics under such conditions, and to determine how **effects of rapid climate change propagate through the terrestrial surface system**, we will peruse precisely dated sediment and biological archives throughout Europe and adjacent regions to reconstruct hydro-meteorological conditions, ecosystem composition, erosion, and weathering rates, using proxies tuned on modern systems. This will yield calibrated functions linking hydrometeorological changes to their sedimentary and biological records; mechanistic reconstructions of climate-driven tipping points in eco-geomorphic systems; and comprehensive environmental reconstructions of past warm intervals during the Holocene and other interglacials. This research will complement and benefit from work in T2 on climate mechanisms in these same periods.

To explore and constrain the **links between erosion, chemical weathering, and microbial activity** that determine ecosystem structure and matter fluxes at Earth's surface, we will combine field and laboratory observations. Newly developed stable isotope and cosmogenic nuclide methods will be used to fingerprint and determine rates of surface processes. In addition, we will characterize organic matter at the molecular level and track it along transport pathways, and use microbiological methods to explore the mechanisms and impact of microbially mediated weathering. This work will result in an understanding of rock-life interactions from the Earth's surface to the deep underground, enabled by drilling the deep biosphere along a climate gradient and in an active fault system. It will yield constraints on the microbial functions and traits that control soil formation and stabilize the Earth's surface (link with ST1). Moreover, we will deliver an understanding of mineral nutrient cycles in coupled plant-microorganism-rock systems, aided by mass spectrometry of novel isotope systems to fingerprint biogeochemical element cycles. Notably, work in this area will quantify sediment, carbon and solute fluxes from continental sources into coastal systems and the oceans (input for T2, T4 and planned CTA Earth system thresholds affecting CO_2). This will rely on measurements of transit times and location, duration and effects of storage of mobile mass, and will yield insights into changes in global sediment cycles in geological time.

Permafrost thaw alters geomorphology, hydrology, biogeochemistry, and microbiology in rapidly warming Arctic-Boreal regions with complex local to global feedbacks. We will assess permafrost vulnerability to thaw in past, current, and future environments (input for T2, T4 and planned CTA Earth system thresholds affecting CO_2). This will involve reconstruction, observation, and projection of thaw-driven landscape dynamics from field measurements, observatories, mobile infrastructure (MOSES), remote sensing, and modeling. Permafrost-preserved **organic matter**, one of the largest organic carbon pools globally, is prone to mobilization in a warming climate. We will quantify its volume and distribution, assess its composition, origin, history, quality, and lability. **Microbiota** in permafrost drives mobilization of carbon and nitrogen in response to thaw. We will assess how metabolic and taxonomic shifts of microbial communities translate into carbon and nitrogen turnover and net GHG production in thawing permafrost, and characterize new microbial taxa and pathways involved in these processes. We will also model microbial activity based on genomic data from natural thaw-transects and lab simulations. Finally, we will constrain former, current and future pathways of permafrost organic matter including land-to-sea-to-atmosphere transfers of carbon (input for T4 and T2), and estimate biogeochemical cycle feedbacks with ecosystems and global climate. For this, we will measure **GHG emissions** on land and from the air, construct regional data products from observations, simulations, and machine learning, perform trend analyses, and determine causes of variability across scales. Work on GHG fluxes will also be pursued in temperate wetlands, and for the first time in complex landscapes with non-steady sources such as fast eroding mountains. This complements T1 research on GHG fluxes from anthropized settings.

High latitude biodiversity provides various ecosystem services. We will quantify biodiversity-climate-permafrost interactions on annual to glacial-interglacial time scales focusing on state-transitions, trajectories, legacies, and feedbacks. We will estimate taxonomic, functional and phylogenetic biodiversity change during vegetation state transitions using sedimentary ancient DNA analyses; simulate tree-line advance and forest compositional change using an individual-based vegetation model; and quantify high latitude vegetation-climate feedbacks, permafrost, and fire. Glacial and thermokarst **lakes** are geo-biodiversity hotspots. We will identify trajectories of lake systems on millennial to decadal time scales to support projections of future changes. We will gather multi-proxy information on sedimentary fill, hydrology and species assemblies, assisted by development of new stable isotope, geochemical and palaeogenetic proxies. Finally, permafrost regions harbor **diverse land use systems**. We will deliver a first detailed characterization of environmental legacies of past climate that represent the past, present, and future human livelihoods in Russian permafrost areas and feed into the LandTrans simulator.

Deliverables (D) and Milestones (M)

- **D5.8 (2026):** Novel techniques to constrain terrestrial surface attributes and process rates. **M5.8-1 (2025):** Isotopic tools for quantification of weathering and erosion. **M5.8-2 (2025):** Hyperspectral measurements of Earth's surface composition.
- **D5.9 (2026):** Environmental reconstructions of past warm intervals. **M5.9-1 (2024):** Functions linking ongoing hydro-meteorological changes to sedimentary and biological records. **M5.9-2 (2025):** Reconstructions of climate-driven tipping points in eco-geomorphic systems.
- **D5.10 (2026):** Understanding of rock-life interactions from the Earth's surface to the deep underground. **M5.10-1 (2024):** Deep biosphere drilled in key locations. **M5.10-2 (2025):** Mineral nutrient cycles constrained in coupled plant-microorganism-rock systems.
- **D5.11 (2026):** Quantitative understanding of permafrost-climate feedbacks. **M5.11-1 (2025):** Permafrost vulnerability and thaw rates constrained. **M5.11-2 (2026):** Microbial turnover and GHG production rates quantified. **M5.11-3 (2026):** C and N pools and fluxes quantified.
- **D5.12 (2027):** Understanding of high latitude biodiversity and climate interactions. **M5.12-1 (2023):** Biodiversity and tree-line dynamics assessed. **M5.12-2 (2026):** Lake trajectories identified.

Infrastructures and specific resources. Research in ST5.3 will exploit major established and new facilities including the Helmholtz Laboratory for the Geochemistry of the Earth Surface (HELGES), a Fourier Transform-Ion Cyclotron Resonance-Mass Spectrometer (FT-ICR-MS), the Geophysical Instruments Pool (GIPP), the Potsdam Imaging and Spectral Analysis facility (PISA), the Helmholtz Laboratory for Integrated Geoscientific

Biological Research (GeoBioLab), the AWI Ancient DNA Laboratory, the TERENO-NE observatory, the Central Asia observatory, the Taroko Observatory for Extreme Earth Surface Dynamics in Taiwan, the Samoylov Research Station in the Lena delta, and a network of sites for long-term monitoring of geosphere-atmosphere energy, water, and GHG exchanges in the Arctic and Germany, supported by AWI Polar Aircraft. Essential geodetic and hyperspectral data underpinning this research will come from GFZ-coordinated satellite missions, including GRACE-FO and EnMAP.

Cooperation partners. Key partnerships include the Geo.X network of geoscience institutes in the Berlin and Brandenburg region supplying complementary expertise and instrumentation; the Central Asian Institute for Applied Geosciences CAIAG partnering regional hydrological and cryospheric research; Russian institutions helping secure continuity of permafrost ecosystem research; the Academia Sinica and the National Taiwan University, partnering in the Taroko observatory; and Argentinean and Chilean university partners in research into landscape evolution and critical zone dynamics in South America.

Risks and Opportunities. Risks to planned research derive primarily from delay, failure, or premature termination of major infrastructure and data missions. The launch of the EnMAP mission is scheduled for 2020; delay or failure will be compensated by a shift of focus to ground-based and airborne hyperspectral missions. The ongoing GRACE-FO mission is yielding data that will, together with 15+ years of GRACE time series, support our planned research until the end of the Program period, even in the event of premature termination. Delivery of the GeoBioLab, expected for 2020, will place us at the forefront of geomicrobiological research. Establishment of a comprehensive dating facility for Earth surface materials would strategically improve the efficiency and flexibility of research in this Topic.

Subtopic 5.4 SMART models and monitoring

Sabine Attinger, UFZ

Scope and challenges. Regional hydro-meteorological projections indicate an increasing frequency and strength of heatwaves and droughts, e.g., in Southern and Central Europe. This will result in more pronounced low-flow situations in rivers, stronger and longer soil droughts, less groundwater recharge as well as severe urban heat situations and higher river temperatures in summer. The impacts on ecosystems, human health, and the economy seem to be significant due to e.g., losses in crop yields, extreme stress on aquatic systems, higher carbon releases from soils, and more pest infestations in forest systems. Cross-sectoral effects need to be considered, like reduced (river) cooling capacities for power plants, higher energy demand for air condition systems, and higher risks for cardiovascular diseases.

One big challenge is to deliver **terrestrial model systems** with an adequate complexity. On the one hand they need to be seamlessly connected to General Circulation Models (GCM) of the climate modeling community and, on the other hand, they need to provide the necessary details for (multi-sectoral) regional impact assessments and adaptation studies. Moreover, these models need to be 'simple' enough that the available data is adequate for setting robust parameters for the models, but also 'complex' (or mechanistic) enough to be transferred to other regions and scales and provide reliable predictions (we consider this the definition for SMART – Scalable, Mechanistic, of Adapted complexity, Robust and Transferable).

Moreover, all regional models suffer from a chronic lack of detailed process knowledge and specific data to parametrize these models. Therefore, all relevant processes and patterns need to be observed using **model-driven monitoring** approaches, i.e., the layout of the monitoring has to be designed to optimize the predictive ability of models specifically.

In order to operate these high-resolution model chains for projection periods of 50–100 years, we need to employ supercomputers and also quantum technologies in future – a potential future key technology that is not yet developed in the terrestrial modeling. This results in exponentially increasing volumes of output data (big data) which are hard to be analyzed conventionally. Therefore, we need to develop multi-thematic data repositories, apply seamless workflows **and new machine/deep learning methods** to extract usable data information. In order to improve the model efficiency, future data-science methods will be helpful to advance current models through data-driven modeling components. The resulting hybrid models will be less complex but are intended to deliver still good predictions.

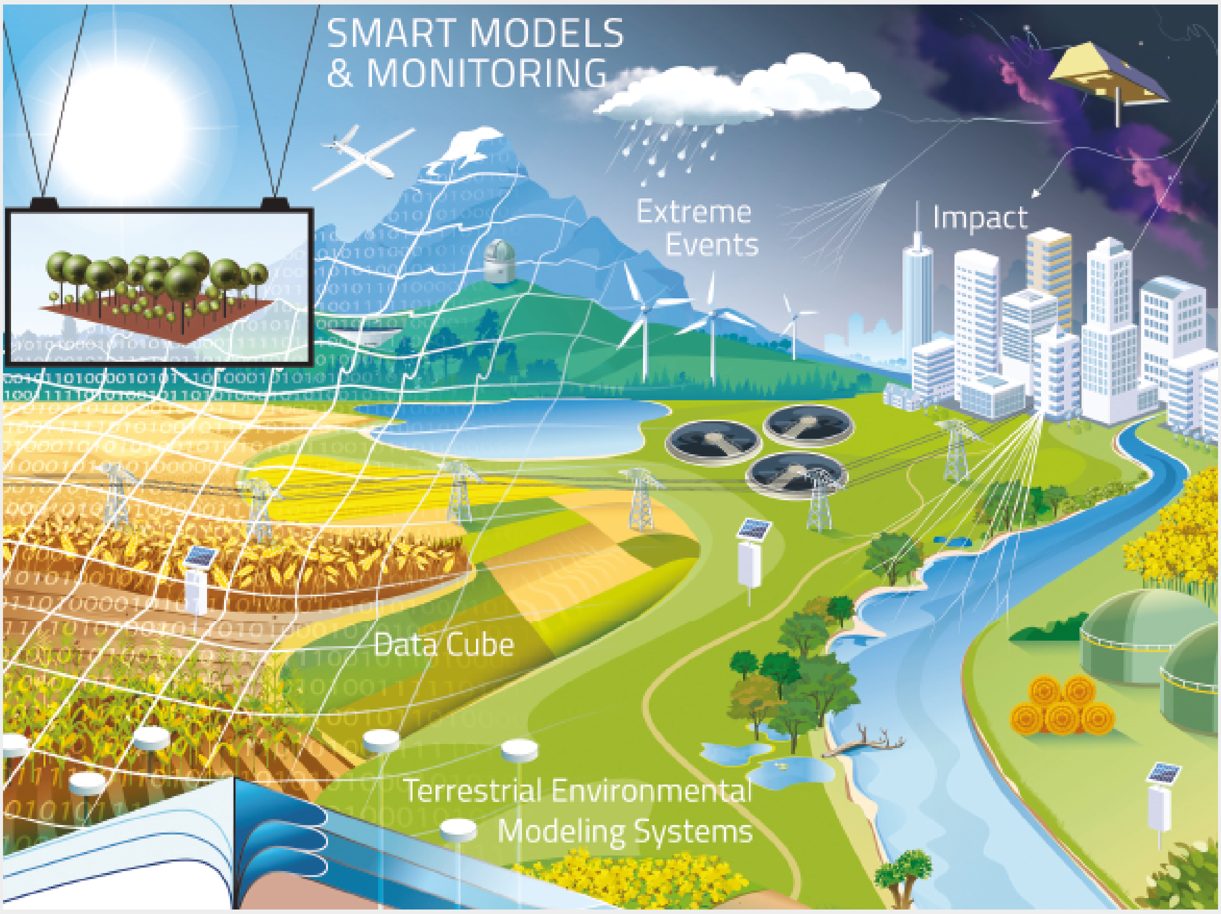


Fig. 5.5: SMART Models and Monitoring. ST5.4 aims to develop robust pictures of the future with an unprecedented richness and resolution. The combination of large-scale climate change, regional land use, and detailed multi-sectoral local impact models is key to this Subtopic with a special emphasis on the impacts of hydro-meteorological extremes and finding sustainable solutions for securing the supply of water, food and raw materials while maintaining the natural life support systems.

Finally, no single terrestrial model will be able to produce the projections that are needed for socio-economic decisions. For instance, interlinked effects of heats and droughts may lead to an increased demand for agricultural irrigation during summer periods with some significant effect on, for example, the groundwater resources. Based on our modeling and monitoring philosophy, we will develop operational **model chains** of necessary complexity that can be used to **maximize cross-sectoral system resilience** by **adaptation to hydro-meteorological extremes.**

Main objectives.

- Developing next-generation SMART terrestrial model systems (TEMS) with an unprecedented richness and resolution for predicting and projecting water quality and quantity, biomass production, energy and biogeochemical fluxes, and storages under global change for Europe but also worldwide.
- Development and implementation of model-driven monitoring strategies, applying a unique combination of new sensor technologies together with data-science methods for regionalizing local observation data.
- Storage and integration of model data, remote sensing, and local observation data in new multi-thematic data repositories and machine-learning inspired data analysis of big environmental data sets.
- With the help of a new generation of computational technology: estimation of sectoral and regional impacts of global and climate change by establishing complete model chains that build on regional climate models developed jointly with all other Topics within the ESM initiative, various TEMS as well as ecological and socio-economic impact models. A complexity-reduced version for specific applications, stakeholders, and decision-makers will be tailored by making use of data-science methods and feeds into the LandTrans simulator to allow for testing different adaptation strategies.

- LandTrans is an overall T5 synthesis product and will synthesize the outcomes of modeling activities which run in collaboration with the other Topics and Subtopics. ST5.4 contributes to T5's research subjects by its joint model development, data collections, and application of data science methods.

Work program. **SMART Modeling Methodology for providing next-generation terrestrial systems models (TEMS):** UFZ model developers from different terrestrial Earth compartments created the SMART concept to solve the dilemma between generality and predictability of regional environmental models (jointly with ST5.1, ST5.2, and ST5.3). This concept is already implemented in the hydrological model **mHM** and the forest model **FORMIND**. It will be extended to the whole TEMS simulating water, energy and matter fluxes and storages also taking biodiversity aspects into account for whole continents in a spatial resolution of at least 1 km^2. The effort will lead e.g., to high-resolution multiscale projections of water quality and aquatic ecosystem status for whole Europe by means of the **m**ultiscale **W**ater **Q**uality **M**odel **mWQM** (jointly with ST5.1, ST5.2, ST5.3, T1, T3, T4), but will also allow projecting combined drought and heat effects on crop yields, water storage and quality, as well as on water temperatures influencing the cooling capacity of river systems or on ecosystem health due to pest infestations. The results will be made available and usable for stakeholders and decision-makers through the overall Topic synthesis product **LandTrans**, the modular simulator of land transitions.

Model-driven monitoring strategies. Relevant data set provision, model-driven monitoring strategies, and sampling designs for regionalizing local measurement data, as well as harmonized data management concepts, are crucial for TEMS development. Since soil moisture is a key variable for hydrology and also for terrestrial ecosystems, the first German-wide measured high-resolution soil moisture product is planned using local and moving cosmic ray sensor techniques, together with AI-driven regionalization and downscaling approaches. The monitoring activities also include the development of an advanced biodiversity monitoring (jointly with ST5.1). ST5.4 will, therefore, enable SMART ways of data to model workflows from terrestrial environmental and ecological long-term observations (input to and jointly with ST5.1, ST5.2) by enhancing existing monitoring concepts to model-driven perspectives, and establish a regional Remote Sensing Center together with the University of Leipzig.

Multi-thematic data repositories and machine-learning inspired data analysis. For the optimal data to model flow chains, it is essential to have high-quality research data management with optimal workflows, from sensors to full information, following prominent international standards like FAIR (Findable, Accessible, Interoperable, Re-usable, input to all Subtopics, jointly with ST5.1, ST5.2). Herewith, the generation and application of multi-thematic data repositories for modeled and observed data play an essential role. For this, ST5.4 will prepare the relevant locally and remotely sensed as well as modeled data from multiple sources into analysis-ready data sets. This will be achieved by flexible and scalable methods preparing a Machine Learning Ready Database for the complex querying of the repositories (input to and partly jointly with STs 5.1 to 5.5) and setting-up workflows to apply data analysis and mining methods to these databases. This enables an optimal extraction of variables that explain and drive observed phenomena (jointly with T4). These variables are then built via deep learning methods into robust prediction modeling systems and will outperform mechanistic models in terms of efficiency.

The estimation of sectoral and regional impacts by establishment of goal-oriented high-resolution model chains. High-precision projections assessing esp. the impact of hydro-meteorological extremes require forming goal-oriented high-resolution impact model chains as well as the usage of new software technologies and next-generation computing power, i.e., exascale and quantum computing, to run these demanding TEMS codes efficiently. Furthermore, the collaboration between the Subtopics will be of focus by performing coupled model runs, designing appropriate interfaces to impact models, make assessments of climate-related risks and vulnerabilities across sectors, and investigate adaptation strategies scenarios under global change. Fast, robust data-driven models trained on both TEMS and observation data will be implemented in the modular simulator LandTrans and hence enable to develop management options or infrastructural planning, like e.g., new management plans for reservoirs to meet future (drinking) water needs. The activities are also highly connected to established future activities of Earth system modeling within the Helmholtz Association (e.g., Pilot & JL-ExaESM).

Deliverables (D) and Milestones (M)

- **D5.13 (2027):** Impact studies with the SMART Terrestrial Environmental Modeling System (LandTrans AGRI and mWQM). **M5.13-1 (2023):** SMART Concept. **M5.13-2 (2025):** mWQM. **M5.13-3 (2025):** LandTrans.

- **D5.14 (2026):** Implementation of SMART monitoring strategies into terrestrial observatories. **M5.14-1 (2022):** Establishing the Remote Sensing Center in Leipzig. **M5.14-2 (2024):** Enhancing existing monitoring strategies by a model-driven perspective.
- **D5.15 (2026):** Readiness and complex applications of FAIR machine learning (ML) ready multi-thematic data cubes. **M5.15-1 (2023):** Data preparation to be machine learning ready. **M5.15-2 (2024):** Workflows for ML and deep learning (DL) analyses of the data cubes.
- **D5.16 (2027):** Fully integrated model chains for sectoral impact studies (impact chains, input to SynCom). **M5.16-1 (2024):** Assessments of climate-related risks and vulnerabilities across sectors. **M5.16-2 (2026):** Investigation of adaptation strategies and scenarios under global change.

Infrastructures and specific resources. ST5.4 will shape the monitoring concepts, sampling strategies, and data standardization of TERENO, MOSES as well as eLTER in conjunction with its TEMS development. Furthermore, it will prepare the model code for exa- and quantum computing at the supercomputing center of the Helmholtz Center Jülich. These adaptations will allow T5 to make frontier simulations to reach new dimensions of future terrestrial environmental-state projections based on scenario assumptions. Furthermore, ST5.4 is in charge of the Helmholtz 'Platforms for Digitalization in Research' (HAICU, HIP, HIFIS) and will contribute by data provision, research data management strategy development, and AI method deployment.

Cooperation partners. The Competence Center for Scalable Data Services and Solutions (ScaDS-Leipzig/Dresden) is an important strategic partner in various data science areas such as interoperable data integration, high-performance computing, and visual data analytics. Furthermore, the Jülich Supercomputing platforms are of high relevance for the model development and model runs. The European Centre for Medium-Range Weather Forecasts (ECMWF) is a strong partner in model evaluation and data provision. Furthermore, partners within the Cosmic Sense Network (DFG-FOR 2694) are of high relevance. HZG-GERICS cooperates in the continuous development of Coordinated Downscaling Experiments (CORDEX) in the frame of the World Climate Research Programme (WCRP). Climate model data is provided through the Earth System Grid Federation (ESGF).

Risks and Opportunities. ST5.4 also relies on modern hardware architectures (i.e., progress in quantum computing), therefore adapting time planning of related software development might be necessary. ST5.4 will deliver worldwide unique high-resolution impact model chains for safeguarding the multifunctionality of terrestrial landscapes.

Subtopic 5.5 Society and the terrestrial environment

Bernd Hansjürgens, UFZ

Scope and challenges. ST5.5 aims to understand and assess the societal framework and case-specific conditions for achieving sustainable multifunctional landscapes. A central element is the analysis of the behavior of individual, economic, and public actors, insofar as it impacts landscapes. Our aim is to develop pathways and suitable policy recommendations for the management of landscapes and how their multifunctionality can be achieved, maintained or restored.

To this end, ST5.5 draws on a broad range of environmental social sciences with strong experience in collaboration with the natural sciences and with stakeholders. Their complementary approaches will be jointly applied to address four challenges of utmost importance both for Germany and globally: i) managing agricultural land use in such a way that resources and multiple ecosystem services can be provided and biodiversity of terrestrial ecosystems can be conserved, ii) minimizing land use impacts of ongoing transitions towards renewable energies and resources, iii) enhancing water management and governance to reach quality requirements of aquatic ecosystems and provide water services under conditions of e.g., climate change and emerging pollutants, and iv) enhance the resilience of cities in their interaction with multifunctional landscapes. Synthesizing research results across these four gateways is a prerequisite that opens up pathways for making landscapes multifunctional.

ST5.5 analyzes how these pressing challenges are conditioned by actor constellations, behavioral patterns, and governance structures. A particular focus will be on decision-making processes at different spatial and temporal scales and how they interrelate. This analysis will generate novel policy options and contribute to multilevel governance of land use management. With profound expertise of science-policy-dialogues (IPCC,

Fig. 5.6: ST5.5 assesses societal impacts and societal drivers of environmental change with a focus on social behavior and governance structures. Coupling such insights with model-based predictions developed in other Subtopics, ST5.5 is in a unique position to explore transformation pathways to sustainability, especially in the fields of biodiversity and ecosystem services, renewable energies, water resources, and urban development.

TEEB, IPBES), ST5.5 will analyze context-specific knowledge needs as well as implementation challenges. Policy solutions that deliver tangible results for achieving and managing multifunctional landscapes and their resources will be designed.

Main objectives.

- Understand the role of human and societal behavior, as well as governance structures for transformations towards multifunctional landscapes; identify unintended side-effects, synergies, trade-offs, and paradoxes within and between transformation fields.
- Synthesize theoretical-conceptual approaches of socio-environmental transformations and empirical insights from, for example, the German *Energiewende* or the paradigm change brought about by the EU Water Framework Directive, to explore the spectrum of preconditions and bottlenecks for successful transformations towards multifunctional landscapes.
- Advance pictures of urban futures under conditions of global environmental change by developing an integrated framework to comprehensively assess the resilience of cities and co-design solutions on how to enhance their coping, adaptive and transformative capacities.
- Complement the LandTrans simulator by assessing anthropogenic drivers and responses to environmental and societal change; include stakeholder and practitioner knowledge in order to develop policy options.

Work program.

Enhancing ecosystem service opportunities in multifunctional landscapes. Our research on agricultural landscapes recognizes that the much-needed behavioral change of relevant actors requires suitable policy instruments to create adequate conditions ('ecosystem service opportunities') to move towards sustainable land use.

Against this background, we will assess policies and governance structures in order to develop sound **policy recommendations** that facilitate such transformations. We will contribute to the LandTrans simulator by disclosing societal costs and benefits of alternative land management approaches and their impacts on soils, ecosystems, and freshwater resources. A second contribution to LandTrans will consist of advancing agent-based models that allow for identification and assessment of different policy options for altering land management decisions. We will provide policy recommendations for e.g., the reduction of agricultural non-point source emissions to freshwater resources, or enhanced enforcement of regulations making use of digitalization (ST5.1 and ST5.2) within the framework of the European Common Agricultural Policy (CAP) and its national implementation.

Sustainable renewable resources and energies 2050. Our research on renewable resources (bioenergy, solar and wind power) will build on assessing decision-making about renewables in highly uncertain and regionally different landscape contexts. We will contribute to the development of **spatially explicit scenarios** for the site-specific allocation of renewable resources. Building on this, we will develop **indicators and governance arrangements** that improve the applicability, comprehensiveness, and reliability of renewable policies in Germany. Our focus will be on i) energy sector coupling, ii) the nexus of energy with material use, iii) cascading issues of new bio-based materials, and iv) the nexus between new bio-based materials and bioenergy with carbon capture and storage. We will integrate these streams of research into ST5.4 by spatially explicit modeling and into CARF BmE and T7 by life cycle assessment of renewable energies and bio-based products. Our research on renewable resources in landscapes contributes to the analysis of human and societal drivers, impacts and governance options aiming to identify preconditions and policy instruments for the ongoing transformation of the German energy system ('Energiewende'). On the international level, we will develop scenarios to demonstrate to what degree renewable energies and renewable resources conflict with or contribute to the SDGs.

Water sustainability pathways 2030plus. In the context of water management, we will collaborate with ST5.2 and ST5.4 and focus on **integrating societal drivers into water-system analysis**. In pursuit of water quantity issues, we will develop socio-hydrological agent-based modeling that will contribute to the assessment of climate-related risks and vulnerabilities, such as impacts on water-dependent agricultural land. We will analyze the food-water-energy nexus in arid and developing regions in order to develop adaptation strategies. Addressing water quality, we will develop hydro-ecological management approaches that take into account the entire water cycle and relevant socio-economic conditions of river-basin management alternatives. We will enhance recommendations on better implementation and further development of the EU Water Framework Directive – the world's most ambitious 'test-case' of ecologic water governance – supporting a more effective and cost-efficient management of multiple water pollutants. To help underpin sustainable urban water management as an integral part of multifunctional landscapes, we will develop governance frameworks and designed solutions for 'blue-green' infrastructures in urban and urban-rural areas.

Transformations towards resilient cities. Cities and urban areas do host the majority of the population, human-made infrastructures, and economic assets. They are drivers and recipients of extreme climate events and global change. Integrated frameworks are needed for a systematic assessment of the exposure and vulnerability of cities and their inhabitants, the integrity of urban infrastructures, and the cities' potential in a circular economy. We will **analyze decision-making processes to support the coping capacities of the affected population as well as infrastructure development and the design of policy instruments to make cities more resilient.** For example, our research on extreme events will contribute to the development and assessment of climate adaptation strategies. We will also identify paradoxes that might emerge from unexpected and unintended outcomes of different policies and adaptation measures. ST5.5 will contribute to the CARF Resilient Urban Spaces with research on blue-green infrastructures, the development of governance mechanisms for the transformation of urban areas, and scenario analysis and modeling of extreme events.

ST5.5 will **synthesize insights on transformations towards multifunctional landscapes** based on our four foci (ecosystem service opportunities, renewable resources and energy, water sustainability pathways, and resilient cities), particularly focusing on the role of enabling factors.

Deliverables (D) and Milestones (M)

- **D5.17 (2026):** Policy instruments and governance options to enhance ecosystem opportunities in agricultural landscapes. **M5.17-1 (2024):** Agent-based models to assess policy options to alter land management decisions (input to LandTrans). **M5.17-2 (2024):** Recommendations for agricultural policy in the EU.

- **D5.18 (2027):** Scenarios, indicators and governance arrangements for renewable resources and energies (bioenergy, wind, and solar). **M5.18-1 (2022):** Spatially explicit modeling and life cycle assessment of renewable resources and energy at the landscape level in Germany (input LandTrans). **M5.18-2 (2024):** Analysis of drivers, impacts, and governance options for a successful transformation of the German energy system. **M5.18-3 (2026):** Policy recommendations for achieving the SDGs for renewable energies and renewable resources.
- **D5.19 (2026):** Societal drivers and policy options for water management. **M5.19-1 (2024):** Socio-hydrological multi-agent modeling to assess climate-related vulnerabilities and to identify adaptation strategies in the food-water-energy nexus (input to LandTrans). **M5.19-2 (2024):** Co-designed solutions for 'blue-green' urban water infrastructures. **M5.19-3 (2025):** Systemic analysis of managing multiple water pollutants (input to MACE).
- **D5.20 (2026):** Decision-making processes and policy instruments for making resilient cities. **M5.20-1 (2024):** Development and assessment of climate adaptation strategies for urban areas. **M5.20-2 (2024):** Detection of emerging paradoxes from attempts to achieve conflicting societal goals (e.g., SDGs). **M5.20-3 (2024):** Lineup of transformation pathways for resource-efficient, livable, and resilient urban areas.
- **D5.21 (2027):** Identify barriers and catalysts of transformations towards sustainability.

Cooperation partners. With our strategic partner **Deutsches Biomasseforschungszentrum – DBFZ** we exchange data and model results for a wide range of biomass/bioenergy technologies and facilitate access to the energy and agricultural sectors (Federal Ministries of Food and Agriculture, for Economic Affairs and Energy, and of Transport and Digital Infrastructure). With our partners at **Utrecht University**, the Swiss Water Research Institute **EAWAG**, and **Harvard University** (S. Jasanoff), we advance transformation concepts that foster innovative pathways towards sustainability.

Risks and Opportunities. Depending on how the European Common Agricultural Policy (CAP) will be implemented in Germany, research opportunities may emerge from requests for policy advice from Federal Ministries Advisory Boards and NGOs. We see an opportunity to become a hub in urban resilience research. Given that our social science research is concerned with conflict-laden environments, there is the risk that our methodologies and survey methods require adjustments to safeguard the privacy of individuals and the confidentiality of data collected.

E) Previous achievements of the contributing centers and infrastructures

Expertise and preliminary work. **UFZ**'s contributions to T5 are based on four organizational units of the center, which share outstanding research infrastructures in the fields of Earth observation, experimentation, monitoring, data analysis, modeling, and simulation. The center has established globally unique controlled field experiments (e.g., GCEF), and extended existing observatories and monitoring platforms (e.g., TERENO). The Experimental Research Station Bad Lauchstädt comprises a comprehensive set of complementary biodiversity and ecosystems experiments, and with **TERENO, MOSES, and MOBICOS**, UFZ has gained an outstanding international reputation and leadership in continuous long-term observations. World-leading results in catchment monitoring strategies and in travel time distributions between river corridor and catchment scales have been obtained. Moreover, the UFZ coordinates the implementation and operation of the eLTER RI (see below), and is a leading partner in other national (e.g., BonaRes, Biodiversity Exploratories) and global networks (e.g., NutNet, Drought-Net) investigating the sensitivity of terrestrial ecosystems to increasing global change. In order to close the chain from integrative, process-based research to policy advice, the UFZ has developed and applied novel modeling concepts integrating heterogenous goal-oriented data, and data-science approaches. Joint-up monitoring, observation, and experiments on selected field sites have underpinned a new generation of scalable, high-resolution, predictive coupled-modeling approaches. Hydrologic modeling at the UFZ has advanced the international state-of-the-art.

The UFZ runs **Integrated Projects**. These fixed-term, problem-oriented and interdisciplinary organizational units draw expertise from across the center's research units to pursue scientific excellence through coordinated, inter- and transdisciplinary research. Social science disciplines have systematically been included. Special incentives have been used to strengthen synthesis research through a combination of top-down and bottom-up procedures. This has resulted in leadership of numerous **EU integrated projects**, as well as key contributions to state-of-research reviews in biodiversity, climate change, and SDGs. UFZ scientific results serve as input in international programs and scientific advisory bodies, including **IPBES** (Intergovernmental Platform for Biodiversity and Ecosystem Services) and **IPCC** (Intergovernmental Panel on Climate Change), and in water policy advice to the **EEA** (European Environmental Agency) and **UNEA** (United Nations Environmental Assembly). The integration of a broad range of social science disciplines allows the UFZ to tackle environmental challenges in context-specific real-world settings, based on transdisciplinary cooperation with decision-makers and stakeholders. New scientific and societal debates (e.g., TEEB – The Economics of Ecosystems and Biodiversity, or the inclusion of spatial considerations in the field of renewable energies) have been triggered through this mechanism.

GFZ contributes broad expertise of Earth surface processes and dynamics, ranging from paleo-hydrometeorology, hydrology and hydro-gravimetry, environmental geophysics, geomorphology, and Earth surface process modeling, via isotope and organic geochemistry to geomicrobiology. GFZ's Earth surface research comprises all space-time scales from deep geological time to the present day, from the nanoscale to interactions between Earth system compartments. Examples of recent path-finding GFZ research include: sub-annually resolved climate and environment records from lake and tree archives spanning periods of rapid change; numerical models performing rapid analysis of controls on landscape evolution; superconducting gravimetry for hydrological sensing; regional-scale flow routing and flood risk models; a microbial cultures collection for cold environments; seismic monitoring of distributed erosion processes; combined constraints on denudation and weathering rates from the $^{10}Be/^{9}Be$ ratio. This work provides fundamental insights into the dynamics of the Earth surface system, and thresholds and tipping points across all time scales, helping anticipate effects of future human impacts.

In addition, GFZ brings its global leadership in the preparation, operation, data provision, and research from satellite missions, driving geodesy, gravity field monitoring and modeling, and hyperspectral remote sensing. Examples include the EnMAP hyperspectral mission and the GRACE gravity field missions. The latter drive first-time space-based studies of the hydrological cycle, with daily solutions offering the prospect of, for example, monitoring floods from space.

AWI has leading expertise in integrated permafrost ecosystem research, ranging from the reconstruction of long-term permafrost ecosystem dynamics, and the observation and quantification of current periglacial and ecological processes, to the prediction of future permafrost ecosystem transitions in a warming climate and under disturbance regimes. Field-based investigations in remote areas of Siberia, Canada and Alaska form the core of AWI's environmental research. They are matched with cutting-edge work in palaeogenetic, biogeochemical, hydrochemical and stable isotope laboratories and remote sensing and process-based modeling capabilities. The reputations of the AWI lead researchers are confirmed by a starter and a consolidator ERC grant in this field.

The **HZG**-based Climate Service Center Germany **GERICS** is pioneering concepts for science based climate services, building on extensive expertise in high-resolution regional climate modeling and analyses of mean and extreme climate changes. GERICS develops local climate information and prototype products with a strong focus on urban adaptation.

Uniqueness. T5's systems-based approach to the multifunctionality of landscapes integrates the natural and social sciences, it reaches across compartments, spatial, and temporal scales and socio-economic sectors, and it matches natural dynamics with human interventions. T5 will identify functional synergies, analyze conflicts between development goals and strategies, and minimize non-intended side effects in cross-sectoral syntheses. It covers the whole chain of knowledge creation, from detailed process-based knowledge in the natural sciences via coupled modeling to the assessment and provision of policy strategies in the social sciences. T5 experts hold operational responsibility for, and have access to, a comprehensive range of high quality research infrastructures and long-term observatories. The development of a new generation of models and simulators will be advanced, and mechanisms of knowledge transfer enhanced.

F) Collaboration and transfer

Partners. Beyond cooperations with many German and leading international universities (e.g., international hub on land use research with Vrije Universiteit Amsterdam, or modeling with Purdue University), T5 partners with the **German Centre for Integrative Biodiversity Research (iDiv**, including the close collaboration with **HIFMB**), funded by DFG and UFZ. Integrating three universities (Halle, Jena, Leipzig), UFZ and seven Max Planck and Leibniz Institutes into a world-class research center, iDiv advances biodiversity science across time and spatial scales, levels of complexity and disciplinary boundaries. In sDiv, the Synthesis Centre of iDiv, international and interdisciplinary synthesis teams address main objectives shared with T5. Together with the **Potsdam Institute for Climate Impact Research** (PIK), UFZ adresses societal relevant questions in the field of global change and regional climate impacts.

Strategic cooperation with the U.S. **Socio-Environmental Synthesis Centre SESYNC** aims at bridging between natural and social sciences through theories, data, and models. This collaboration has addressed the integration of the human dimension in Earth systems models and the coupling of models to assess *systems of systems*. Cooperation with the **Stockholm Resilience Center** covers the analysis, governance, and management of social-ecological systems to enhance the capacity to deal with complexity and change, with a focus on sustainable land management.

T5 will contribute to shaping the European environmental research agenda by facilitating knowledge exchange and joint projects within the **PEER – Partnership for European Environmental Research**, of which UFZ is a founding member. T5 cooperates with German and international environmental agencies, i.e., UBA, BfN, EEA, and UNEP's World Water Quality Alliance.

Within the field of Earth system modeling, T5 cooperates with international partners like the National Center for Atmospheric Research – **NCAR**, University of Princeton, Lawrence Berkeley National Laboratory and Center of Ecology and Hydrology **CEH**, contributing its unique infrastructures. Cooperation partners contribute to model development and benchmarking. For example, the expertise of large-scale hydrological modeling is provided by the **Global Institute for Water Security**.

T5 partners in several international remote sensing and data initiatives: The US National Aeronautics and Space Administration, **NASA**, and GFZ partner in the **GRACE** and **GRACE-FO** satellite missions, collecting global gravimetric data in support of hydrological research. The German Aerospace Center, **DLR**, is a key partner for a broad range of remote sensing and GeoData science, focusing on natural land surface dynamics in this Topic. DLR partners GFZ in the **EnMAP** hyperspectral satellite mission, which will yield data on the composition of the Earth's surface and its change. Regional model hindcast simulations are based on **ECMWF Reanalyses Data**. AWI runs **Pangaea®**, a leading publisher worldwide for Earth and environmental data.

Positioning of the Topic in international research. T5 is bringing a uniquely wide range of **disciplines from across the Earth and life sciences** to bear on the processes and links within the Earth's terrestrial surface system. Together these disciplines range from the nano- to the global scale, and from the present into deep geological time, with proven interfaces and effective combinations of geo- and bio-approaches. This ensemble is underpinned by a comprehensive range of laboratory infrastructure and observatories and observation platforms that enable long-term monitoring of remaining natural, sensitive, and highly dynamic settings and global trends. The systems approach of this ensemble can only be matched elsewhere by multi-institutional consortia that tend to be ephemeral in nature.

Reaching farther, T5 matches its comprehensive Earth and Life Sciences approach with a three-pronged **social sciences** strategy to tackle environmental problems in their crucial, societal dimension. It does so by i) integrating the way natural sciences look at environmental problems, and ii) connecting the social dimension to real-world problems (with compounded ecological scales, different levels of governance and various sectors), whilst iii) using expertise from a broad range of social science disciplines. This approach differs from most social science groups globally. T5 has specific strengths in science-policy interfaces on the EU (and international) level, procedures for knowledge synthesis, multi-level governance, and policy-mixes (i.e., the interactions of taxes, legal regulations and spatial planning, for example) in the fields of biodiversity, renewable energy, water, and urban transformations.

With its research **strategy on landscapes of the future**, the Topic has a unique position, linking innovative sectoral aspects and placing them in a new system context. This is achieved in particular by the integration of experimental, observational, and modeling platforms with social science applications, the results of which will be incorporated into SynCom.

Notably, T5 research builds on an unrivaled **range of infrastructures** (see above). Coordinating the ESFRI eLTER RI, T5 has access to a network of about 200 observatories across Europe, securing first-class terrestrial environmental monitoring, surveillance and research. eLTER's fundamental approach is to observe and analyze the environmental system from biological, geological, hydrological, and socio-ecological perspectives. In the long-term, eLTER will harmonize its strategy with complementary continent-wide observation networks such as US NSF NEON and Australia's TERN, to achieve a global network of terrestrial observatories.

Cross-Cutting Activities and Alliances. The **TERENO** infrastructure provides a platform for the analysis of the interactions and feedbacks between the several compartments of the terrestrial environment. T5 uses the TERENO Harz and TERENO Northeastern German Lowland Observatories to study hydrological and landscape processes with particular focus on water quality and water storage dynamics for human use (reservoirs), as well as the long-term effects of land use change on biodiversity, groundwater-surface water interactions, GHG budgets, and long-term lake and vegetation responses to climate change.

T5 contributes significantly to **MOSES** on climate extremes and their impact on landscapes, focusing on heavy rains and floods, heatwaves and droughts, and abrupt permafrost thaw. T5 contributes novel approaches for distributed process monitoring 'from source to sink' and model coupling to improve the predictions of weather extremes' impacts on all affected Earth systems and the consequential socio-economic risks as addressed by REKLIM and the HI-CAM.

Remote Sensing. T5 focuses on the observation of land use changes, surface water resources, floods and droughts, and infrastructures in and outside urban areas, e.g., extraction of vegetation dynamics and land use intensity and classification, satellite product validation, process-based phenological modeling, radiative transfer modeling, multi- and hyperspectral remote sensing applications, and multi-sensoral application for essential biodiversity variables.

Exascale Earth System Modeling (JL-ExaESM). T5 will address and support progress towards solving the computational and data challenges posed by future supercomputers and contribute to new software paradigms for the next generation of Earth system models.

ESM. T5 contributes to ESM by developing Earth System Modeling & Analysis Frameworks as well as data assimilation tools, and frontier simulations in cross-cutting areas like hydro-meteorological extremes and cross-compartment matter cycling. In addition, ESM is the basis for code development and application towards exascale and quantum computing. Model evaluation and validation will be performed with remote sensed Earth observation data, enhancing T5's abilities in model development on large scales.

Digital Earth. Simulations, models, and monitoring infrastructures developed and maintained by T5 will play a fundamental role in the DE Showcase Hydrological Extremes. In turn, DE will support T5 by providing workflows for monitoring designs, e.g., securing data flow from sensors in multiple Earth compartments to analysts, and data exploration, building on machine learning and visual analytics.

Digitalization. T5 is involved in five Helmholtz platforms for the digitalization in research (i.e., HIDA, HAICU, HIP, HMC, and HIFIS). Moreover, T5 is highly involved in national and Helmholtz activities enhancing research data management (e.g., EOSC, GoFAIR, RDA, and SaxFDM).

HI-CAM's adaptation cluster is coordinated by UFZ and broadly based on T5's expertise in completing chains of impacts and of knowledge, coping mechanisms to extreme events like floods and droughts to water management, biodiversity, and soils. Hence it will develop extremely detailed impact scenarios or projections to fulfill the need for timely decision-making to create adequate adaptation measures.

REKLIM. T5 contributes to three overarching activities in REKLIM: i) the land surface in the climate system, ii) modeling and understanding extreme meteorological events, and iii) risk analysis and risk management for integrated climate strategies.

Resilient Urban Spaces. T5 will help drive this Cross-Cutting Activity and contribute with research on blue and green infrastructures, elements of a circular economy within cities and in the urban-rural nexus, governance mechanisms for the transformation of urban areas, and scenario analysis and modeling of extreme events and impact chains.

Earth system thresholds affecting globally relevant CO_2 sources and sinks. T5 contributes to this planned CTA mechanisms and quantifications of carbon fluxes from the terrestrial Earth surface to the atmosphere and oceans, their sensitivity, characteristic time scales and associated feedbacks.

Extremes. T5 contributes regional climate impact modeling and research on vulnerability and coping capacities of individuals and society with respect to floods and droughts.

MACE. T5 will identify social factors impacting human health, and, with respect to ecosystem health, study cause-effect relationships of chemicals in inland waters.

Bioeconomy meets Energy. T5 will provide spatially explicit renewable energy and biomass scenarios and assessment for Germany by i) improving life-cycle based assessment of ecological, economic and social sustainability aspects and ii) analyzing the trade-offs and conflicting targets from a systemic view.

Transfer and contribution to SynCom. With its extended synthesis approach, that integrates individual compartments, socio-economic sectors, different spatial and temporal scales, and stakeholder knowledge, T5 will be instrumental for SynCom. T5 has a strong emphasis and longtime experience on knowledge transfer[172] that goes beyond traditional forms of (unilateral) transfer and includes the co-design and co-development of mutual knowledge exchange processes right from the beginning of projects; stakeholder services (e.g., climate services, soil-related services, water quantity and quality services[173]) are an integral part of T5. The involved social science disciplines play a key role in developing tailored stakeholder-oriented solutions and implementable policy options.[174] The process of strengthening knowledge transfer and knowledge exchange within the Helmholtz Association and beyond was initiated and has been shaped by T5. Based on this expertise, T5 will provide key contributions to scientific synthesis (e.g., the modular simlator of transitions LandTrans), and in the networks mentioned above (e.g., coordinating the initiative and taking the lead of HI-CAM's adaptation cluster). T5 will contribute to task forces and foresight processes within SynCom. Further contributions may include: enhancing capacities of urban areas to cope with climate extremes; a masterplan how to halt biodiversity loss; management plans on pathways how to secure water resources and aquatic ecosystems in selected developed, newly industrializing and developing countries.

Executive Summary

- T5 provides a unique platform for synthesizing pathways towards multifunctional landscapes of the future. These landscapes can sustainably deliver the many and diverse services demanded by society, even under intensifying pressures, while retaining their natural capacities to fulfill their vital role in the Earth system. This will be achieved by combining natural with social sciences, as well as process monitoring in a multitude of observatories with new modeling strategies for analyzing impact chains.
- T5 contributes to several Program objectives on biodiversity, ecosystems and related provisioning services (5, 6, 7), better impact predictions (1), climate (2, 3), and livable spaces for humans (4, 5, 9). Reaching across compartments, socio-economic sectors and scales, T5 demonstrates how desirable pictures of the future can be made attainable (10).
- T5 is focused on terrestrial landscapes as spaces where human impacts, ecological alterations, and social costs of land use changes and effects of climate change directly shape human life. Since the human dimension has become pivotal in this arena, T5's approach will exemplify how knowledge-based recommendations, adaptation strategies, management plans and policy instruments maintaining and restoring multifunctional landscapes can be developed and assessed on various levels (from global to regional) along the whole **chain of knowledge creation.**

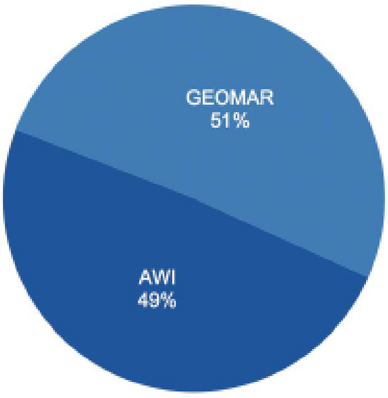
[172] See above, e.g., contributions to IPBES, IPCC, EEA, UNEA.

[173] An example is the German Drought Monitor: https://www.ufz.de/index.php?en=37937, or the Climate Office for Central Germany at UFZ.

[174] See above, e.g., science-policy interfaces on national and international level, procedures for knowledge synthesis, multi-level governance, and policy-mixes.

Topic 6: Marine and Polar Life: Sustaining Biodiversity, Biotic Interactions and Biogeochemical Functions

Spokespersons: Ute Hentschel-Humeida, GEOMAR; Bettina Meyer, AWI



Topic 6 will provide the scientific foundation for a sustainable management of the ocean by determining the functions and dynamics of marine ecosystems and assessing options to remedy and mitigate human impacts. Topic 6 will study the diversity, structure and functioning of the marine biosphere, investigate how marine organisms and ecosystems will adapt and respond to human impacts and assess to what extent the uptake of CO_2 by the marine biosphere and the biogeochemical cycles in the ocean are affected by climate change. Our research will cover all levels of biological integration, from genes to ecosystems, and will integrate knowledge on the entire ocean system from the equator to the poles.

A) Scope and challenge of the Topic

Research subject. Marine and polar life is affected by anthropogenic perturbations, such as increasing temperatures, sea ice decline, decreasing pH values and oxygen contents, resource extraction, fisheries, and pollution. As a result, fundamental impacts are expected on marine biodiversity, community organization, species performance, ecosystem functionality and services, and the global carbon cycle.

Using compatible sampling and experimental approaches in different habitats from polar, over temperate to tropical oceans, we aim to resolve unifying principles of organismal and community responses to climate change and their role in shaping biogeography and species interactions based on taxonomic and trait-based groupings. Such fundamental ecological and evolutionary studies are the basis to project how marine biota mediate and control the cycling of carbon, oxygen and nutrients in the global ocean and the CO_2 uptake from the atmosphere. Topic 6 (T6) will evaluate strategies for marine governance and conservation by comprehensively assessing the biological and biogeochemical consequences of ocean change (Fig. 6.1).

Explanation and justification of research. Covering 70% of Earth's surface, the oceans harbor the last seemingly pristine ecosystems on our planet. But in fact, only 13% remain that qualify as 'wilderness',[176] while most ocean ecosystems suffer from growing anthropogenic pressures caused by fisheries and shipping, carbon dioxide emissions, warming, pollution and littering that increasingly compromise the vital ecosystem services to humankind. T6 integrates ecological, evolutionary, and biogeochemical approaches to assess the responses of marine life to environmental change through adaptation, range shifts, and community turnover and how these varied responses impact food webs, carbon turnover and other element cycles in the world's oceans.

[176] Jones KR, Klein CJ, Halpern BS, Venter O, Grantham H, Kuempel CD, Shumway N, Friedlander AM, Possingham HP, Watson JEM. 2018. The Location and Protection Status of Earth's Diminishing Marine Wilderness. Curr Biol. 28:2506–2512.

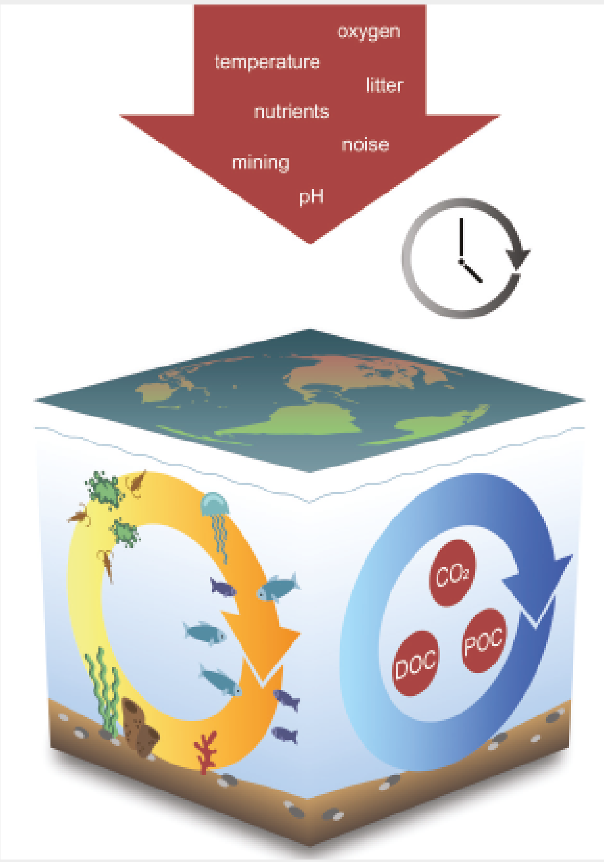


Fig. 6.1: T6 studies the biodiversity, biotic interactions, and biogeochemical functions of marine ecosystems and their response to global change. It aims to protect marine ecosystems and the services that they provide to humankind by establishing the scientific basis for sustainable ocean management.

Strategic guidelines (FoPoZ). Understanding the emergence, distribution and diversity of life-forms and their complex interactions with the biotic and abiotic environment is critical to ocean management and conservation, but remains one of the great challenges to science and society. T6 will provide scientific knowledge needed to improve regulations for marine environmental protection by assessing the response of marine ecosystems to human pressures and communicating the scientific results to policy makers, regulators, maritime industries, environmental NGOs and the general public. T6 will provide instrumentation, data infrastructures and personnel for specific missions of DAM and MARE:N, and will directly contribute to the United Nations Sustainable Development Goal (UN SDG) 14 'Life Below Water'.

Function and contribution of the Topic within the Program. As a Topic dedicated to marine life, T6 is linked to T4 and T5 with respect to energy and matter flow from terrestrial to marine systems, which passes through coastal regions. Moreover, many of the studied processes such as ecosystem functionality and adaptation are studied in coastal and open ocean ecosystems in a coordinated and comparative way. T6 will cooperate closely with T2 to integrate cutting-edge ocean physics into biological and biogeochemical field studies and models. Moreover, T6 will deliver an assessment of the carbon cycle in the modern ocean as reference for the reconstruction of past carbon budgets to T2 and it will reciprocally receive paleo-reconstructions from T2 to validate its biogeochemical ocean models. Close interaction and co-coordination are also envisaged with T5, using cross-ecosystem analysis and synthesis to i) find commonalities and differences in changing terrestrial, marine, and freshwater life, and ii) address cross-system fluxes of matter and organisms. Knowledge on marine biodiversity, ecosystem functioning, and biogeochemical cycles generated in T6 will be used in T7 and T8 to guide the sustainable use of biological and mineral resources.

Highlights.

MOSAiC. Seasonality of cryopelagic life and biogeochemistry in the Central Arctic Ocean will be studied by the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC). The flagship activity will provide an unprecedented data set covering an annual cycle in and below the pack ice of the Central Arctic Ocean. Most importantly, it will cover the seasonal composition and activity of the biological system and related element cycles to changes in temperature and light availability. T6 and T2 activities within MOSAiC are closely integrated and will cover spatial and temporal variability at multiple scales. Modeling activities will support upscaling of mechanistic and small-scale understanding and will provide a tool to predict the future biological productivity of the Central Arctic Ocean.

HIFMB. The urgent need for integration of marine biodiversity research motivated the foundation of the Helmholtz Institute for Functional Marine Biodiversity (HIFMB) at the University of Oldenburg. The HIFMB will install four new professorships and develop the scientific basis for marine conservation and marine ecosystem management by analyzing the functional role of biodiversity in marine ecosystem. The institute thereby establishes the necessary knowledge and tools to predict future changes in biodiversity and ecosystem function and to analyze their consequences for human well-being. The Helmholtz Institute will develop novel concepts for marine conservation, with particular emphasis on a theoretical framework of conservation that considers three-dimensionality and spatio-temporal dynamics of the marine habitat. Regarding the practical planning process, models for the trade-off between conservation objectives and ecosystem services will be developed considering stakeholder views.

Pan-Atlantic Ocean change. T6 provides for the first time a framework for the full integration of the biological and biogeochemical research conducted at AWI and GEOMAR. The high and low latitude work that is conducted by these partners in the Atlantic will be integrated to provide the first synoptic view of the Atlantic ecosystem and its response to global change from the equator to the poles. This Pan-Atlantic synthesis will integrate all relevant results obtained by Subtopics 6.1-6.4. Furthermore, T6 will reach out to T2 and T4 to integrate changes in ocean physics and marginal sea dynamics in this synthesis effort.

B) Main research and structural objectives

Research Objectives.

- **Objective 1:** Understand the role of marine biodiversity in maintaining marine ecosystem processes and services under variable environmental conditions.
- **Objective 2:** Assess ecological and evolutionary adaptation and dynamic responses of marine species and ecosystems to anthropogenic perturbations, including the identification of 'winners' and 'losers', and specific community shifts.
- **Objective 3:** Understand how CO_2 uptake by marine ecosystems responds to and affects present and future climate change, with a focus on the biological carbon pump and ocean productivity.
- **Objective 4:** Assess how plastic debris, anthropogenic noise and harmful substances spread in the ocean and affect marine ecosystems as well as their services to society.
- **Objective 5:** Contribute to IPCC, IPBES, UN SDG 14 and the United Nation Decade for Ocean Science (2021–2030) by providing the data, information and scientific basis for the assessment of climate change impacts and the implementation of sustainable ocean management.

Structural Objectives.

- **Objective 6:** Establish T6 as an international leader in marine biology, biogeochemistry and functional biodiversity by providing a common framework and synergies for the respective research at AWI and GEOMAR and the newly founded HIFMB.
- **Objective 7:** Foster the integration of German marine sciences by closely cooperating with the national initiatives MARE:N and DAM.
- **Objective 8:** Strengthen interdisciplinary Earth System Sciences by working together with the other research Topics of the Program (in particular T2, T4 and T5) via the CCAs ESM, MOSES and Digital Earth, and via integrated data analysis and knowledge transfer.
- **Objective 9:** Intensify cooperation across centers, with T2 and the RF Aeronautics, Space and Transport in the field of innovative sensor technologies (i.e., biogeochemical sensors, robotics and remote sensing).

C) Structure of the Topic and motivation of Subtopics

Introduction of Subtopics. T6 is composed of four Subtopics (STs) with critical links to other Topics and strategic partners (Fig. 6.2).

ST6.1 on **'Future ecosystem functionality'** will identify general principles in the relationships between functional biodiversity and major ecosystem processes and determine the mechanistic background of the response of biodiversity and species interactions to natural variability and global change. It will develop sustainable conservation and management strategies to mitigate consequences of global change by e.g., assessing strategies to establish and manage marine protected areas (link to T4). ST6.2 on **'Adaptation of marine life: from genes to ecosystems'** will focus on the dynamic responses of marine species to ongoing anthropogenic perturbations. The main objective is an integrative understanding of responses at the molecular, cellular, organ, organismal and holobiont level. The outcomes of adaptation processes are in turn critical for ecosystem functioning, information that will feed into ST6.1. ST6.3 on the **'Future biological carbon pump'** will study how marine ecosystems facilitate the sequestration of CO_2 in the ocean. Employing the knowledge gained in ST6.1 and ST6.2, ST6.3 will investigate how CO_2 uptake and turnover by marine ecosystems respond to ongoing and future climate change, and will collaborate with T2 on past ocean carbon fluxes and climate. ST6.3 will contribute to the overall Program by assessing fluxes of CO_2 and other climate active gases across the atmosphere/ocean boundary, one of the major interfaces of the Earth system. ST6.4 on **'Use and misuse of the ocean: Consequences for marine ecosystems'** will study how plastic debris, anthropogenic noise and harmful substances released during deep-sea mining and ordnance disposal spread in the ocean and affect the habitat of marine organisms. Building on the approaches and results of ST6.1 and ST6.2, ST6.4 will investigate how marine ecosystems respond to these direct human interventions and how adverse effects can be minimized by improved ocean management. All Subtopics will implement innovative technologies including sensors, platforms and data science methods.

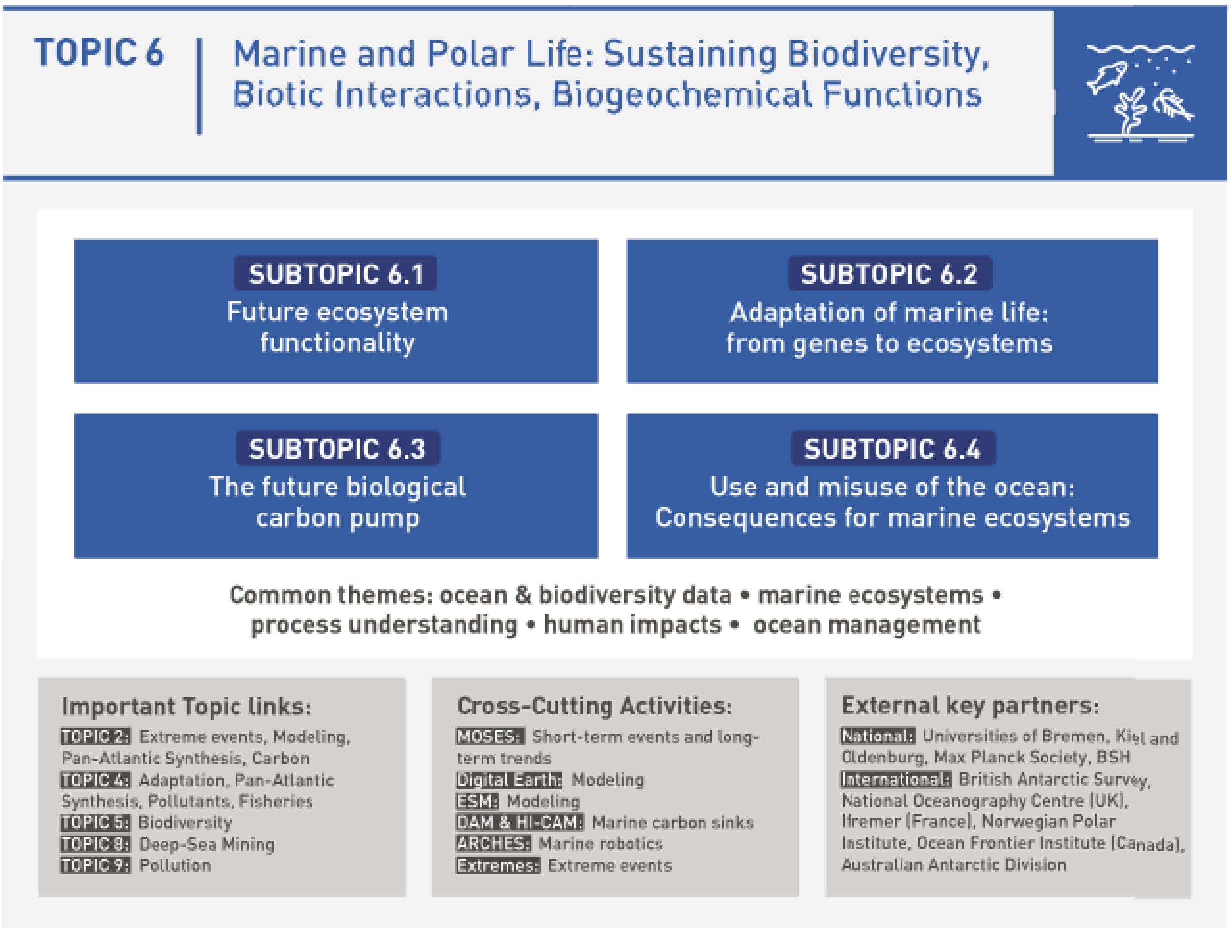


Fig. 6.2: Graphical scheme of T6 with critical links to Cross-Cutting Activities and strategic partners.

Contribution of the Centers to the Topic. The contribution of **AWI** to ST6.1 is through the newly established HIFMB, which includes i) quantification of biodiversity change and its drivers, ii) empirical assessment of functional consequences of biodiversity change, and iii) natural and social science-based concepts of marine conservation and governance. AWI provides long-term monitoring activities, such as the Frontiers in Arctic Marine Monitoring (FRAM) observatory at Long-Term Ecosystem Research (LTER) observatory Hausgarten and flagship projects such as MOSAiC to improve the understanding of ecosystem processes through field campaigns and will concentrate their activities on the interaction between ocean and sea ice dynamic in a warming climate. In ST6.2, AWI will focus on the role of genotypic versus phenotypic plasticity of key species at both poles (e.g., krill, copepods, phytoplankton, codfishes). It will be addressed, how the environmental history of the Antarctic vs. Arctic determines species' reaction norms and adaptation to climate change (e.g., diatoms, krill) and which implications these have for biodiversity and ecosystem functioning. In ST6.3, AWI will investigate Arctic and Antarctic whole basin nutrient and carbon budgets, the impact of plankton communities and key species on export of carbon and nutrients as well as mechanisms how microbial activity and trace element cycling control Southern Ocean primary production and carbon export using in situ observations, remote sensing and numerical modeling. AWI's contribution to ST6.4 includes the investigation of the pathways of plastics, on spatial and temporal scales, and in different ecosystem compartments, implementing a risk assessment matrix for microplastics. The noise field of natural intact underwater acoustic environments versus less pristine environments will be studied for implementing a soundscape baseline from pristine Antarctica.

GEOMAR researchers will contribute to all four Subtopics proving state-of-the-art technologies (e.g., MOSES) and data science methods (Digital Earth, ESM, and MarDATA). In ST6.1, GEOMAR will provide input to species inventories of open and deep-sea habitats using novel imaging technologies coupled with eDNA assessments and metagenomics as a first step to characterize biological interactions and matter fluxes in the open and deep ocean. A strength of GEOMAR is the research of adaptation in marine organisms, where it will take the lead to address the objectives outlined in ST6.2, including in-depth genomic, meta-genomic and meta-transcriptomic assessments of species interactions and ecological adaptations. This is complemented by AWI's expertise in meta-metabolomics and analytical chemical ecology of organismal interactions. Results on the time dimension of organismal adaptation will provide important foundations to project future ecosystem functionality (ST6.1). In ST6.3, GEOMAR will assess drivers of carbon export and provide flux measurements at the atmosphere-ocean and seafloor-ocean interfaces, measure the biological carbon turnover within the ocean, and provide calibrated biogeochemical ocean models simulating the biological carbon pump under a range of global change scenarios. GEOMAR will contribute to ST6.4 by characterizing the environmental impacts of deep-sea mining and ordnance disposal and the fate of plastic debris in the ocean. Through the Cape Verde Ocean Observatory (CVOO) and the Ocean Science Centre Mindelo (OSCM), GEOMAR provides long-term research and observation capabilities in the eastern tropical North Atlantic Ocean, a region with high vulnerability and feedback potential.

D) Subtopics

Subtopic 6.1 Future ecosystem functionality

Helmut Hillebrand, HIFMB; Katja Metfies, AWI

Scope and challenges. A major societal challenge of the current century is to ensure a sustainable provision of essential ecosystem services under the combined pressures of growing human populations, increasing resource demands, and unprecedented rates of biodiversity change. For marine ecosystems, we still lack a mechanistic understanding of the response of biodiversity and species interactions to natural variability and anthropogenic changes of the environment, as well as of the causal links between biodiversity and specific marine ecosystem functions and services. Closing these knowledge gaps is critical for the development of effective and sustainable conservation and management strategies to remedy or mitigate consequences of global change and protect marine ecosystem functionality in the future, which remains one of the great challenges to science and society alike.

Main objectives. The central goal of ST6.1 is to understand the role of functional biodiversity in maintaining particular and essential marine ecosystem processes under variable environmental conditions and to identify general principles in the relationships between functional biodiversity and major ecosystem processes (Fig. 6.3). Based on this knowledge, ST6.1 further aims to investigate existing and provide data, information, and new concepts for marine conservation and governance.

Work program. In order to provide the scientific basis for the development of efficient marine conservation and management strategies, ST6.1 will combine regular observational and process-oriented field studies and controlled experiments with theoretical conceptions, numerical modeling, and socio-economic analyses. Such a comprehensive approach is needed to develop efficient strategies for marine governance and conservation. ST6.1 simultaneously addresses multiple dimensions of biodiversity (taxonomic, functional, genetic) to infer general patterns and mechanisms that are required for upscaling. Modeling efforts will support understanding and prediction on ecosystem scales incorporating spatial and temporal variability of environmental drivers and processes. A basic approach of the intended field work is to establish novel dedicated 'exploratories' for comparative large-scale and long-term functional biodiversity research, which combine observational time series investigations, process studies and controlled in situ experiments on cruises and at selected LTER sites across a latitudinal gradient. This includes on the one hand subtropical gyres and upwelling areas through GEOTRACES sections and further cruises, and on the other hand high latitude sites such as LTER Hausgarten and the MOSAiC experiment in the Arctic, as well as the FRAM observatory at LTER Hausgarten for year-round long-term observation and analysis of polar marine biodiversity. Marine biodiversity including microbiomes as well as species interactions and coexistence will be studied across different dimensions of biodiversity and spatio-temporal scales, using the latest approaches, particularly acoustic, optical and imaging methods, modularized experimentation and data analysis techniques (under special consideration of molecular data). Special attention will be paid to ocean warming impacts including the fate of sea ice and processes of multi/micro-nutrient limitations, which may be key in determining the responses of phytoplankton community structure and productivity.[176] The embedding of the resulting data within ocean models (with ST6.3) will lead to

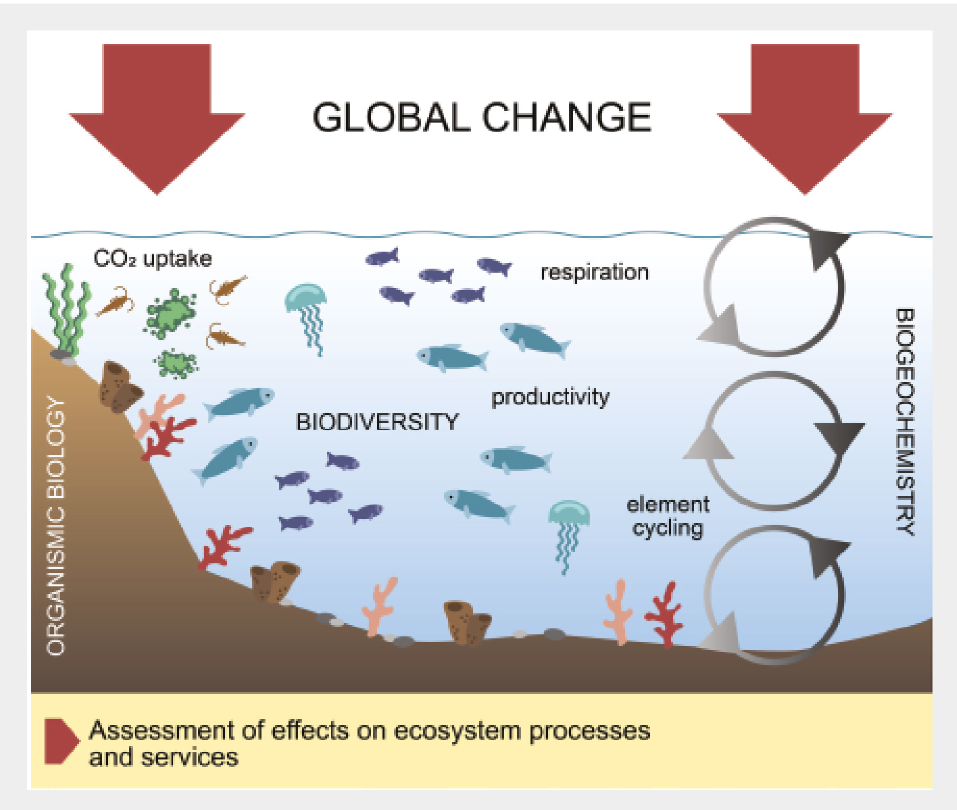


Fig. 6.3: Research objectives of ST6.1: Future ecosystem functionality.

[176] *Browning TJ, Achterberg EP, Rapp I, Engel A, Bertrand EM, Moore CM. 2017. Nutrient co-limitation at the boundary of an oceanic gyre. Nature. 551:242–246.

more realistic projections of feedbacks regulating climate and marine food webs. The resulting information will serve as a basis to develop spatio-temporal scenarios of changing polar biodiversity. The integrated measurement of important physical, chemical and sea ice variables are a direct critical link to T2 and the inclusion of coastal observatories to T4.

Research on biodiversity-ecosystem function relationships is a major facet of current ecology, driven by the concern about human-induced changes in biodiversity. In this context, ecosystem functions encompass all processes and properties of ecosystems constraining matter and energy fluxes, trophic transfer and productivity. Current research aims to identify and quantify causal links between biodiversity, and specific marine ecosystem functions and services such as primary production and carbon flux (with ST6.3). We aim to further develop this research line towards quantifying the robustness of marine communities and ecosystem functionality towards environmental change. In this respect, we need to empirically identify indicator species and critical functional traits (with ST6.2) and model non-linear dynamics to better understand the change in the functional role of biodiversity in marine ecosystems.

Our research strategy considers a broad range of marine life from long-lived, ecosystem-structuring species (e.g., top predators, foundation species such as krill, seagrasses, corals or macro-algae) to microbial taxa that perform important ecosystem functions through their coupling with other organisms and with geochemical cycles. HIFMB will enable ST6.1 to provide integrated knowledge on the role of networks and interactions in ecosystem functionality. So far, these have been mainly dealt with as direct trophic interactions, but other mutualistic interaction types and indirect effects in networks are emerging as central nodes of how biodiversity affects ecosystem functions and how conservation measures can harness future ecosystem services (see below). In this respect, ST6.1 will address interaction networks from metabolic to ecosystem scales, and assess the adaptability of such networks under changing conditions (link to ST6.2).

By linking theory to novel ecosystem informatics pathways, the functional consequences of network changes will be addressed at the basis of individuals, populations, communities and ecosystems. At the same time, we will establish basic understanding of how network configurations and adaptability contribute to ecosystem resilience, and which aspects of networks remain highly vulnerable bearing the risk of crossing thresholds. Such understanding of how specific ecosystem functions emerge will provide the scientific basis for marine conservation to ensure the sustainability and resilience of marine ecosystem services. This will lead to integrative strategies for sustainable management of marine ecosystems and marine governance and conservation, e.g., the development and establishment of a marine protected area in the Antarctic Weddell Sea managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

ST6.1 will establish the necessary knowledge by providing an inventory of tools used to manage marine ecosystems under predicted future changes in biodiversity and ecosystem function and to analyze the consequences of such management strategies for human well-being. In close linkage to T4, the suitability of spatial approaches to marine conservation, as is standard in terrestrial conservation, will be scientifically assessed, including strategies to establish and manage marine protected areas. One central aspect here is forecasting, i.e., basing conservation measures not only on the present status, but the projection into the future of drivers (ST6.4), processes (ST6.3) and adaptive capacity (ST6.2). Focusing on the conservation of biodiversity as well as ecosystem services (providing food, maintaining conditions for human life, securing resources and creating space for recreation and tourism) requires explicit consideration of common (service-providing) and rare (endangered) species. Therefore, ST6.1 will apply a multidimensional concept of resilience that will allow us to better understand the implications of changes in the functional dynamics of ecosystems for human societies through shifts in biodiversity.

Potential trade-offs exist between conserving rare species and those providing ecosystem services. Thus, it is important to assess which species or functional groups have and will suffer most in terms of having become rare relative to a more pristine reference situation. Moreover, the HIFMB will provide direct assessments of the governance of marine systems in national and international contexts. A broad range of approaches from natural and social sciences will be vertically integrated from basic research on evolutionary and ecological constraints of marine biodiversity to implementation in conservation and management strategies and the embedding in society's needs and advances. This objective will be explicitly addressed in a Cross-Topic approach including coasts (T4) and terrestrial as well as freshwater ecosystems (T5).

Deliverables (D) and Milestones (M)

- **D6.1 (2025):** Synthetic overview of how changing abiotic conditions impact marine biodiversity, species distribution and interactions. **M6.1-1 (2022):** Modularized experiment to global change response in phytoplankton based on resource supply changes under changing conditions performed. **M6.1-2 (2024):** Marine network information inferred from general assessment of molecular and other marine long-term biodiversity data across regions. **M6.1-3 (2025):** Spatio-temporal scenarios for high latitude marine biota and their response to multiple environmental stressors developed.
- **D6.2 (2027):** Improved projection capabilities of future marine biodiversity and its role in maintaining key ecosystem functions such as productivity. **M6.2-1 (2022):** Evidence for gradual responses versus non-linear dynamics (e.g., tipping points) and identification of thresholds generalized. **M6.2-2 (2024):** Novel marine ecosystems including their species composition and functionality assessed. **M6.2-3 (2026):** Key linkages between metabolic and species networks in marine ecosystems identified.
- **D6.3 (2027):** Strategies for sustainable management of selected marine ecosystems. **M6.3-1 (2022):** Inventory of management strategies for the marine realm completed. **M6.3-2 (2024):** Trade-off in the role of rare and common species for conservation and ecosystem service provisioning and its future resilience. **M6.3-3 (2027):** Spatio-temporal assessment of governance in the marine realm finalized, taking into account the consequences of connectivity and isolation.

Risks and Opportunities. The target research areas of ST6.1 are extremely complex and spatially heterogeneous systems. Hence, we are challenged to apply appropriate approaches and models that are able to deal with stochasticity and missing data (ST6.3). These risks have to be seen alongside with the fact that recently multi-pressure consequences of anthropogenic actions and climate change for the environment reflected by extreme weather phenomena, overfishing of the seas or pollution of the marine environment with plastics (ST6.4) are becoming apparent. This may lead to a significantly increased societal and political awareness that will help to provide and maintain a solid scientific base for the development of efficient ocean management strategies.

Subtopic 6.2 Adaptation of marine life: from genes to ecosystems

Thorsten Reusch, GEOMAR; Uwe John, AWI

Scope and challenges. Global change impacts organismal physiology, population dynamics, species interaction and ecosystems processes across all spatial and temporal scales in the ocean. How organisms and species cope with these changes constitutes a fundamental aspect in the integrated understanding of marine ecosystems and their functional biodiversity. What has been neglected in marine ecology thus far due to the complexity of research are the different levels of adaptation with time from genes to key species, their populations and communities. Essentially, the species of tomorrow may not react and interact the same way as those of today. The major challenge of this research theme is to elucidate causal mechanisms and interdependencies at different levels of 'adaptation' across biological organization and habitats to identify general principles of adaptation processes on different biodiversity scales. To this end, ST6.2 integrates physiological acclimation across different life stages, evolutionary adaptation at the population level, and community compositional shifts (the latter process in close interaction with ST6.1). Another key goal is to determine how environmentally driven changes may alter key species interactions, including their effects on the functional role of associated microbes, and in turn, how species' range shifts result in strong and novel ecological interactions and evolutionary change.

Main objectives. We are only beginning to understand how and to what extent species compositional change will take place through natural range shifts in response to climate change. Different dispersal capabilities among polar and marine species will result in altered community composition because some species will be able to migrate with their climate range in real-time, while others with poor dispersal capabilities will lag behind. The change in biodiversity, biogeography and re-assembly of biological communities is expected to accelerate across all latitudes and will result in modified and novel biological and chemical interactions which in turn constitute novel selection regimes. This may not only drive adaptation, but also affect functional biodiversity in general (ST6.1), biogeochemical cycles in particular (ST6.3) and overall ecosystem functionality. In order to predict species range shifts, an understanding of water movements and dispersal tracks is indispensable (link to T2). Causal links between drivers of global change and adaptation processes will be addressed on all levels of biological organization, from genes to ecosystems. Combining field studies and experiments with dedicated species-interaction models will generate the required mechanistic understanding of responses to and impact of different climate change scenarios from the organismal to the population and community level (Fig. 6.4).

Work program. Global change physiology and acclimation. An integrative understanding of responses at the molecular, cellular, organ, and organismal level including different life stages to environmental changes requires an assessment of inter-individual variability in environmental acclimation and adaptation over the entire life-cycle of a species, which will be linked to the underlying (epi)genomic polymorphism. A mechanistic, physiological understanding of the impact and interactions of ocean warming, sea ice decline, acidification, nutrient shifts, and hypoxia will be obtained by using selected key species, groups, and communities from our core locations, which are the regional seas of Northern Europe, the polar oceans and in the tropics (Cape Verde).

The plasticity of organisms in response to climate-induced environmental stressors will be identified on the one hand by studying the presence of endogenous clock systems[177] that regulate important daily and seasonal life cycle events[178] in marine key organisms, which drive ecosystem functioning (e.g., krill, copepods, salps,

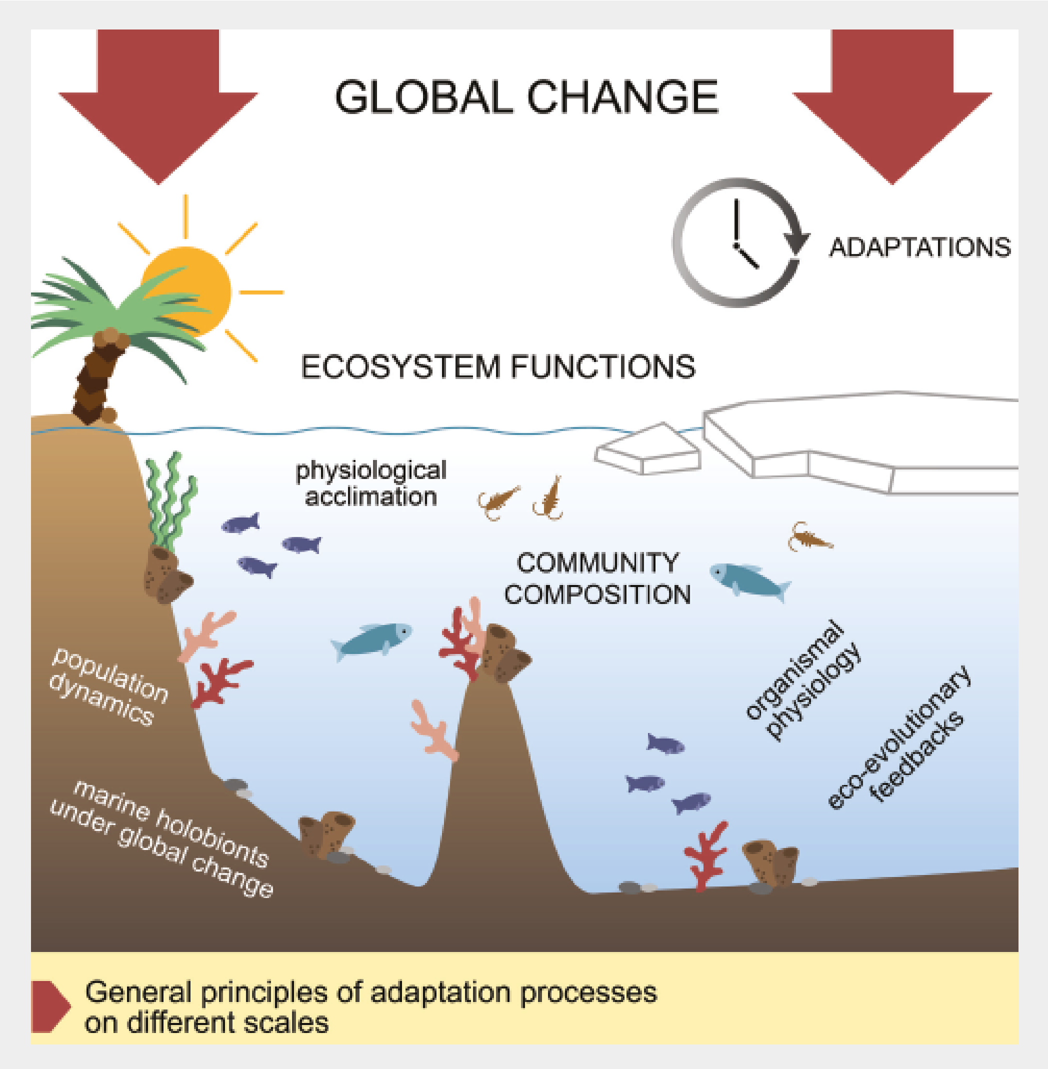


Fig. 6.4: Research objectives of ST6.2: Adaptation of marine life: from genes to ecosystems.

177 *Biscontin A, Wallach T, Sales G, Grudziecki A, Janke L, Sartori E, Bertolucci C, Mazzotta G, DePitta C, Meyer B, et al. 2017. Functional characterization of the circadian clock in the Antarctic krill, Euphausia superba. Sci Rep. 7:17742.

178 *Piccolin F, Suberg L, King R, Kawaguchi S, Meyer B, Teschke M. 2018. The seasonal metabolic activity cycle of Antarctic krill (Euphausia superba): evidence for a role of photoperiod in the regulation of endogenous rhythmicity. Front Physiol. 9:1715.

codfishes, diatoms). Another focus is the sensitivity to thermal, oxygen, and acidification stress and their combined effects. In terms of ocean warming, we will follow IPCC scenarios that are shared by other Topics of the Program (1.5°C, 2°C, 4°C, and 6°C). Potential limits to adaptation will be explored by studying dispersal processes with physical oceanographers (T2) that determine gene pool mixing and major mass extinction events in the geological past exemplifying failed adaptation. To this end, we will apply geochemical proxies to reconstruct changes in environmental conditions that led to the extinction of major marine taxa. ST6.2 will assess how polar and open ocean food webs of the future will function in terms of transfer efficiency under altered composition and interactions with strong implications for the top of the food web and services to humankind, i.e., fishes and fisheries. This task will be performed in close collaboration with T4 and T5, which will also explore, model and predict novel food webs of the future in coastal marine, terrestrial and freshwater habitats.

Marine holobionts under global change. The intimate association of all marine life with microbial communities is a recent major discovery in marine ecology and evolution, and may pave the way to understand the evolution of other holobiont systems on land, including humans. The functional implication, that all species constitute holobionts rather than unitary organisms[179] has to be understood mechanistically and functionally in terms of cross-communication, currency exchanged and inheritance pathways. Microbiomes exert significant ecological impact and their functions for uni- and multicellular hosts will be investigated along the continuum from pathogenic/parasitic to beneficial. Host-associated microbiomes are also expected to have a strong effect on long-term adaptability. ST6.2 aims to identify unifying principles of the adaptation of marine holobionts under global change, using meta-omic tools, high-resolution microscopy, metabolomics and controlled experimentation in selected marine microalgae and invertebrates such as mussels, sponges, cnidarians and ctenophores.[180] Selected polar, temperate and tropical species will be developed into experimental models of host-microbe interactions. The main deliverable will be an assessment under which global change scenarios beneficial host-microbe interactions break down into dysbiosis.

Evolutionary winners vs. losers. While there is increasing data with respect to physiological sensitivity of taxa to thermal regimes or ocean acidification, we know very little about the capacity of marine species to respond by adaptive evolution.[181] Hence, key model organisms in sea ice, pelagic and benthic habitats (planktonic algae, marine invertebrates, macrophytes, fishes, corals, brachiopods and other calcifying organism) will be investigated with respect to what extent they will cope with long-term impacts of global changes over multiple generations. Potential future changes will be deduced from past adaptation observable by comparing populations or phylogenetic groups along a latitudinal cline. Genotypic variability will be linked to phenotypic plasticity, based on an integrated assessment of physiological key traits, transcriptomics, and individual variability. This will be done in a comprehensive way along climate gradients and hot spots of climate change, such as polar regions but also regional temperate seas such as the Baltic Sea that can serve as a time machine for other ocean areas.[182] The final deliverable will be a predictive assessment as to which species groups (functional /taxonomic) are likely to keep pace with environmental change and which will likely go extinct, in a comparative analysis among polar, temperate and (sub)tropical regions. Selection must not necessarily operate only via changing abiotic conditions. A key research arena will be novel species interactions (ecology) that emerge, range shifts or species introductions and how these lead to rapidly evolving novel adaptations in defense or predation ability (evolution). Host-pathogen interactions are another area where ST6.2 research will study rapid antagonistic evolutionary adaptation in real time, with direct ecological consequences when key species are driven to (near) extinction or develop resistance.

Eco-evolutionary feedbacks. Given that there are now compelling examples of swift evolutionary adaptation from algae, invertebrates and fishes, studies on the feedback loops among evolutionary adaptation and

[179] *McFall-Ngai M, Hadfield MG, Bosch TCG, Carey HV, Domazet- Lošo T, Douglas AE, Dubilier N, Eberl G, Fukami T, Gilbert SF, et al. 2013. Animals in a bacterial world, a new imperative for the life sciences. Proc Natl Acad Sci USA. 110:3229–3236.

[180] *Pita L, Rix L, Slaby BM, Franke A, Hentschel U. 2018. The sponge holobiont in a changing ocean: from microbes to ecosystems. Microbiome. 6:46.

[181] *Dahlke FT, Butzin M, Nahrgang J, Puvanendran V, Mortensen A, Pörtner HO, Storch D. 2018. Northern cod species face spawning habitat losses if global warming exceeds 1.5°C. Sci Adv. 4(11):eaas8821.

[182] *Reusch TBH, Dierking J, Andersson HC, Bonsdorff E, Carstensen J, Casini M, Czajkowski M, Hasler B, Hinsby K, Hyytiäinen K, et al. 2018. The Baltic Sea as a time machine for the future coastal ocean. Sci Adv. 4:eaar8195.

ecological interactions are urgently needed to predict future ecosystem functionality. If for example calcifying plankton cannot maintain the capacity to build calcareous scales or shells under progressing ocean acidification, the impact will affect biogeochemical cycles (ST6.3), thus prompting the need for an 'evolutionary biogeochemistry' that explicitly includes adaptation potentials into biogeochemical models. Model systems for such approaches include primary producers (phytoplankton), habitat foundation species such as bivalves, corals, macrophytes (in a joint coordinated effort with T4), as well as species with strong top-down effects on the entire food chain and under direct human exploitation (i.e., fish, cephalopods).

ST6.2 research will also provide urgently needed basic information on whether assisted evolution may be a tool to enhance local resilience of species and ecosystems.[183] This concept will be tested using coral and macrophyte systems under extreme abiotic events in collaboration with T4. We will study whether pre-selection in the laboratory, hardening/long-term acclimation and manipulation of the associated microbiota (cf. holobiont concept) may enhance the resilience and ecological performance of key habitat building species. Our study of eco-evolutionary feedbacks will also encompass human-induced selection, for example, the evolutionary change in critical life-history traits observed in many harvested fish species driven by the size selectivity in fishing gear. The rapid inadvertent 'breeding' of individuals with earlier maturity that stay smaller has major consequences for the functioning of food webs that need to be quantified, while the recovery time needs to be determined. The final deliverable will be an assessment along with proof of principle data on how eco-evolutionary coupling will affect the resilience of key populations (fish) or communities (with macrophytes/sponges as basal species) that are providing key ecosystem services to humankind (ST6.1).

ST6.2 will combine field surveys with experimental approaches from ecophysiology, ecology, and experimental evolution at the single organism up to the community level. We will apply a complex set of 'omics' approaches from transcriptomics, population genomics and epi-genomics, metabarcoding and metagenomics, over proteomic analyses to metabolomics examinations. We will use comparative 'omics' in selected groups to find genomic indicators of adaptability versus evolutionary stasis. Machine-learning algorithms will be utilized to distill signals of molecular genetic selection, or of critical gene expression and metabolites from very large emerging data matrices. Along with large-scale environmental and organismic data from the field surveys, we will generate a comprehensive understanding of organismal and ecosystem responses to the different global change scenarios. We aim to unravel unifying principles of organismal response to climate change and their role in shaping biogeography and species interactions based on taxonomic and trait-based groupings.

Deliverables (D) and Milestones (M)

- **D6.4 (2025):** Predictive assessment as to which species groups (functional/taxonomic) are able to keep pace with environmental change and which will shift range or go extinct, in a comparative analysis among polar, temperate and (sub)tropical regions. **M6.4-1 (2022):** Novel experimental and observational approaches established to study adaptation. **M6.4-2 (2024):** Key adaptation processes and species prone to successful adaptation identified. **M6.4-3 (2025):** Key constraints to adaptation such as low population size/conflicting selection/swamping by dispersal identified.
- **D6.5 (2025):** Predictive assessment under which global change scenarios beneficial host-microbe interactions break down into dysbiosis. **M6.5-1 (2022):** Selected polar, temperate and tropical species will be developed into experimental models of host-microbe interactions; **M6.5-2 (2025):** Identification of critical messenger molecules.
- **D6.6 (2027):** Assessment on the importance of eco-evolutionary coupling for maintaining ecosystem function and marine biogeochemical cycles (link to ST6.1 and ST6.3). **M6.6-1 (2023):** Adaptation including ecological feedback identified in key species; **M6.6-2 (2025):** Modeling marine primary production with and without adaptive processes (ST6.3).

Risks and Opportunities. An inevitable risk complicating any successful synthesis of adaptation processes is the diversity of marine life in itself, including its complex life stages and varied holobiont forms. The targeted selection of key study species, species interactions and communities on the one hand, while keeping

[183] van Oppen MJH, Oliver JK, Putnam HM, Gates RD. 2015. Building coral reef resilience through assisted evolution. Proc Natl Acad Sci USA. 112:2307–2313.

the broader picture and synthesis in mind will be challenging. Evidently, ST6.2 will need to find an intelligent strategy of selecting a few systems where researchers cut deep, while at the same time trying to cover several different key functional taxonomic groups and habitats in a coordinated and joint effort to deliver our goals. We envisage that we closely collaborate with T4 to have a complementary set of coastal study species, interactions and communities. Establishing novel model systems to study holobiont processes of host-microbe interactions under controlled conditions is not trivial and may require years. A particular challenge of this ST is the ever-increasing amount of data in particular in terms of genomics, and metabolomics, which require a new generation of (doctoral) researchers fluent in such multivariate, large-scale data analyses. ST6.2 is actively pursuing a strategy to enhance capabilities in that arena, for example by contributing several bioinformatics projects to the MarDATA Helmholtz Data Science School, and by engaging in Helmholtz Inkubator and NFDI processes focusing on bioinformatics and metadata. A huge opportunity is that researchers working from tropical to polar regions are integrated in one coordinated Program. Likewise, our approach to conduct research on many levels of biological organization, from genes to ecosystems, and with close collaboration of marine and terrestrial studies is unique and will help integrating marine biological sciences.

Subtopic 6.3 The future biological carbon pump

Morten Iversen, AWI; Anja Engel, GEOMAR

Scope and challenges. Marine ecosystems drive the biological carbon pump where phytoplankton converts dissolved inorganic carbon (DIC) into organic matter that sinks or is subducted into the ocean's interior creating a deficit in DIC and CO_2 in the surface ocean. This deficit is replenished by CO_2-uptake from the atmosphere leading to an overall reduction in atmospheric CO_2 levels by ca. 200 ppm.[184]

ST6.3 will study the biological carbon pump, its link to the physical pump and its response to global change[185] over the entire ocean system (Fig. 6.5). A comprehensive assessment of the biological pump will require a multidisciplinary approach utilizing numerical modeling, ship-based studies, in situ experimentation, remote sensing, autonomous underwater observations, smart sensors, meta-omic techniques, molecular-level chemical analyses and flux measurement at ocean interfaces.

Main objectives. We aim to i) understand how primary production and the export of organic matter from the surface ocean into the ocean's interior are controlled by the composition and structure of plankton communities and the intricate interplay of their individual members, ii) quantify organic matter consumption in the water column and fluxes to the seabed, and iii) decipher how physical, chemical, and biological drivers affect net primary production, export efficiency, degradation and aggregation processes, organic matter fluxes and the uptake of CO_2 from the atmosphere. Furthermore, together with T2, T4 and our network of partners, we will iv) predict ocean productivity, organic carbon fluxes and fishery yields over a range of IPCC scenarios including knowledge from past variations.

Work program. Environmental controls on organic matter export and fluxes across the ocean/atmosphere interface. Ocean warming, acidification, deoxygenation and enhanced stratification are projected to change the structure of planktonic communities, ocean productivity, export of organic matter, and the CO_2 uptake from the atmosphere.[186,187,188] To decipher these complex physical-chemical-biological couplings, we will perform multidisciplinary studies on the functionality of the biological pump in the Arctic, Southern Ocean and in eastern boundary upwelling systems. We will employ novel Biogeochemical-Argo floats, ice and deep-sea moorings and landers equipped with e.g., optical, oxygen, pH and nitrate sensors to provide insight into

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[184] Marinov I, Follows M, Gnanadesikan A, Sarmiento JL, Slater RD. 2008. How does ocean biology affect atmospheric pCO_2? Theory and models. J Geophys Res Ocean. 113:20.

[185] *Riebesell U, Körtzinger A, Oschlies A. 2009. Sensitivities of marine carbon fluxes to ocean change. Proc Natl Acad Sci U S A. 106:20602–20609.

[186] *Laufkötter C, Vogt M, Gruber N, Aita-Noguchi M, Aumont O, Bopp L, Buitenhuis E, Doney SC, Dunne J, Hashioka T, et al. 2015. Drivers and uncertainties of future global marine primary production in marine ecosystem models. Biogeosciences. 12:6955–6984.

[187] Marsay CM, Sanders RJ, Henson SS, Pabortsave K, Achterberg EP, Lampitt RS. 2015. Attenuation of sinking particulate organic carbon flux through the mesopelagic ocean. Proc Natl Acad Sci U S A. 112(4):1089–1094.

[188] *Boetius A, Albrecht S, Bakker K, Bienhold C, Felden J, Fernandez-Mendez M, Hendricks S, Katlein C, Lalande C, Krumpen T, et al. 2013. Export of algal biomass from the melting Arctic sea ice. Science. 339: 1430–1432.

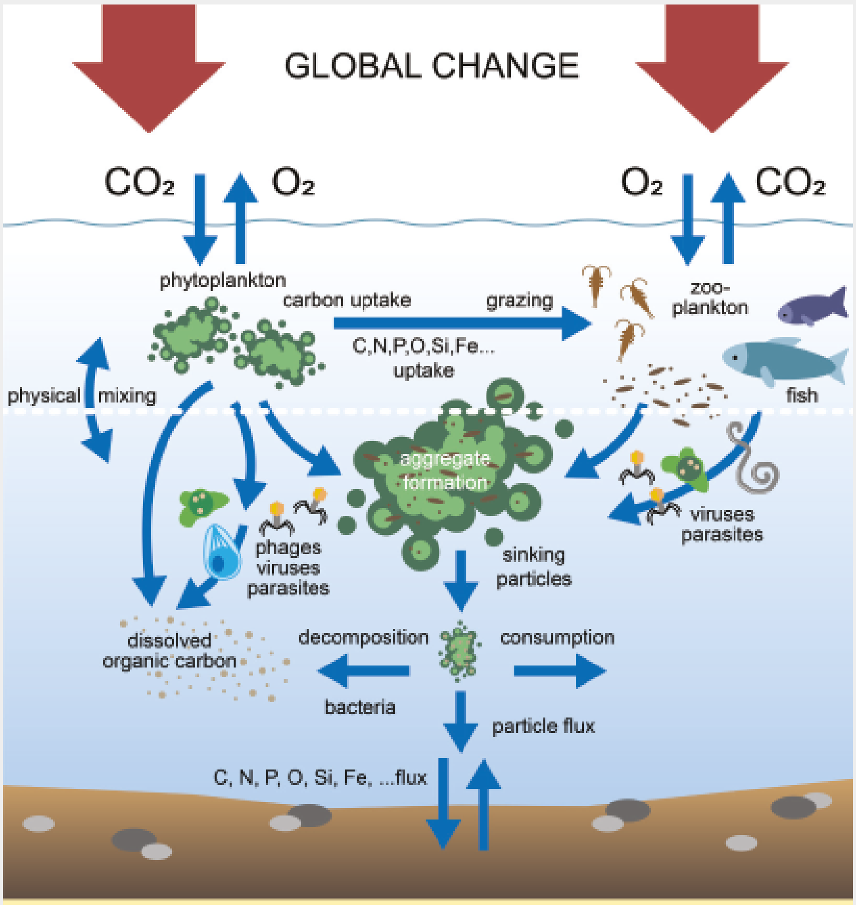


Fig. 6.5: Research objectives of ST6.3: The future biological carbon pump.

combined carbon and oxygen dynamics in the ocean, and use GEOTRACES section cruises to unravel ocean carbon dynamics and their physical-chemical-biological drivers. Changes in the intensity and character of the biological pump will affect air-sea exchange not only of CO_2 but also of other climate-active gases (CH_4, N_2O, oxygenated and halogenated compounds). We will augment the Cape Verde Ocean Observatory (CVOO) with a field laboratory to assess how marine trace gas fluxes respond and contribute to climate change and enhance our contribution to international time series on air-sea interactions. As polar regions are already experiencing some of the most severe regime shifts, we intend to expand our activities in these areas through mooring deployments and process studies in different productivity regimes of the ice-covered Arctic (LTER Hausgarten, MOSAiC) and Southern Ocean. In particular, the Weddell Gyre and its contribution to the sequestration of carbon and nutrients will be investigated through moored instrumentation and shipborne measurements enhancing repeat sections. By linking the biological carbon pump studies with the physical studies in T2, we will assess how GHG fluxes across the ocean-atmosphere interface evolve in a warming climate.

Biological controls on carbon export from the euphotic zone. Linking ocean productivity and food web complexity to export flux and identifying the key biological drivers of vertical transport are high priority research challenges for advancing our understanding of the biological carbon pump. Important biological controls on export efficiency include competition of algal taxa, grazing by protozoans and metazoans, viral lysis of algae, ballasting of sinking organic matter with biominerals, microbial degradation of dissolved and particulate organic matter, and beneficial microbial interactions.[189] These processes also determine the transfer efficiency of algal carbon to higher trophic levels and the formation of refractory dissolved and particulate organic matter.

[189] *Worden AZ, Follows MJ, Giovannoni SJ, Wilken S, Zimmerman AE, Keeling PJ. 2015. Rethinking the marine carbon cycle: Factoring in the multifarious lifestyles of microbes. Science. 347:11.

We will gather data sets of microbial and multicellular plankton ecology covering the seasonal and spatial variability of representative ecosystem types. These data will be evaluated in cooperation with ST6.1 and ST6.2 to explore how classical (direct consumption and movement of carbon to higher trophic levels) and alternative (e.g., parasitism and viral lysis, beneficial interactions with microbes) food web pathways and physiological strategies affect export efficiency. To further unravel these dynamics, we will employ experimental approaches[190] as well as a combination of remote sensing, underwater imaging and field surveys across environmental gradients. Furthermore, we will implement molecular and stable isotope techniques to dissect community composition including microbes and trophic carbon transfer. The knowledge gained will be applied to improve tracer approaches and genomic applications (including environmental DNA) for in situ sensing. Collectively, these studies will allow us to explore how many states, structures, and fluxes are needed to adequately characterize plankton ecosystems and incorporate the biological controls on carbon export in global ocean models.

Carbon turnover in the mesopelagic ocean. Sinking particles are the main vehicle for carbon transport from the surface to the ocean interior. Microbial activity, zooplankton feeding, and particle disintegration/remineralization in the mesopelagic realm further modify particle sinking fluxes below the productive surface layer. The ongoing deoxygenation in deeper layers of the ocean associated with poorly ventilated shadow zones and highly productive upwelling regions will likely result in a reduced attenuation of carbon fluxes, whilst ocean warming may increase attenuation via enhanced microbial degradation accompanied by shifts in microbiome composition. Recent observations show the presence of abundant organic particle aggregates harboring a variety of associated microbial communities in the mesopelagic zone, and suggest that organic matter cycling in the ocean interior is more dynamic than previously thought.[191] This includes the impact of mesoscale features like filaments, fronts and eddies on particulate and dissolved matter distribution at midwater depth and the organic and inorganic matter supply due to diel vertical migrations of zooplankton and nekton.[192]

We will use chemical tracers (e.g., ^{234}Th), sediment traps, marine snow catchers, optical, acoustical and net-based techniques to determine the distribution, composition and stoichiometry of plankton and particles, as well as carbon export fluxes in the mesopelagic at key sites (e.g., CVOO, LTER Hausgarten, MOSAiC, Weddell Sea). A special focus will be placed on the establishment and analysis of year-round synchronous time series observations of relevant parameters using deployed mooring arrays (e.g., sediment flux, particle distribution, physical and chemical parameters), combined with ship-based sampling (e.g., chromophoric dissolved organic matter profiles, high-resolution particle profiling) and usage of autonomous devices (e.g., BGC-Argo floats, AUVs). Analysis of image data from gel traps and in situ imaging units will include the characterization of changes in particle morphology and porosity using machine-learning techniques. Studies focusing on mesoscale feature impacts and degradation dynamics will complement this work and will help us to identify biological, chemical and physical processes that modify particles and hence carbon export efficiencies in the mesopelagic ocean.

Carbon fluxes across the seabed. Seafloor sediments serve as the ultimate sink for carbon provided by the biological pump. Moreover, the rain of particulate organic matter (POM) to the seafloor drives a range of microbial redox reactions that largely control the nutrient (nitrate, phosphate, iron) inventory of the global ocean.[193] Fluxes of POM reaching the seafloor are highly variable both in time and space. Since their spatial and temporal variability was never fully resolved, current budgets of carbon fluxes to the seabed are poorly constrained.[194] To explore the dynamics of benthic POM fluxes and degradation rates, we will develop observatories at the seabed that will register particle fluxes (including large food falls), benthic degradation rates, and bottom current velocities over a full year (at e.g., FRAM at LTER Hausgarten and Cap Verde/West Africa). The

[190] *Riebesell U, Aberle-Malzahn N, Achterberg EP, Alguero-Muniz M, Alvarez-Fernandez S, Aristegui J, Bach LT, Boersma M, Boxhammer T, Guan WC, et al. 2018. Toxic algal bloom induced by ocean acidification disrupts the pelagic food web. Nat Clim Change. 8:1082.

[191] Arrieta JM, Mayol E, Hansman RL, Herndl GJ, Dittmar T, Duarte CM. 2015. Dilution limits dissolved organic carbon utilization in the deep ocean. Science. 348:331–333.

[192] *Kiko R, Biastoch A, Brandt P, Cravatte S, Hauss H, Hummels R, Kriest I, Marin F, McDonnell AMP, Oschlies A, et al. 2017. Biological and physical influences on marine snowfall at the equator. Nat Geosci. 10:852–858.

[193] *Dale AW, Nickelsen L, Scholz F, Hensen C, Oschlies A, Wallmann K. 2015. A revised global estimate of dissolved iron fluxes from marine sediments. Glob Biogeochem Cycles. 29:691–707.

[194] *Soltwedel T, Bauerfeind E, Bergmann M, Bracher A, Budaeva N, Busch K, Cherkasheva A, Fahl K, Grzelak K, Hasemann C, et al. 2016. Natural variability or anthropogenically-induced variation? Insights from 15 years of multidisciplinary observations at the arctic marine LTER site HAUSGARTEN. Ecol Indic. 65:89–102.

spatial variability of POM deposition and degradation will be characterized using advanced seafloor mapping techniques (photo mosaicing, back-scatter imaging, high-resolution bathymetry), environmental DNA analysis, TV-guided lander and benthic crawler deployments, and in situ isotope labeling experiments. The data will be evaluated to provide the first regional budgets of benthic carbon fluxes that fully resolve their temporal and spatial variability. As a first step towards global synthesis, we will compile data sets and grids for seafloor properties and evaluate these grids using machine-learning techniques to generate global maps of benthic carbon turnover in marine sediments. Benthic carbon and nutrient cycling are strongly affected by POM rain rates to the seafloor and oxygen concentrations in ambient bottom waters. We will measure in situ benthic fluxes, characterize microbial communities, and determine turnover rates in different environments covering a large range of productivity and oxygen conditions. Prognostic models will be calibrated by these data and applied to study how benthic carbon and nutrient fluxes respond to ongoing and future ocean change.

Global carbon fluxes and sinks in the modern ocean, climate sensitivity of the physical and biological pumps, and scenarios for future carbon uptake in the ocean. The climate sensitivity of the physical and biological pumps will be investigated quantitatively with state-of-the-art climate models, including the AWI Climate Model (AWI-CM), the coupled physical-biogeochemical model system FESOM-REcoM,[195] the Flexible Ocean and Climate Infrastructure (FOCI), and a hierarchy of marine biogeochemical models. In close collaboration with T2, we will investigate the impacts of changes in circulation, mixing and sea ice coverage on biogeochemical tracer distributions and fluxes. Model simulations will be assessed and calibrated against observations over the past decades,[196] employing novel optimization algorithms and measures of uncertainty.[197a] This is complemented by process-oriented investigations of the role of ocean warming, acidification and deoxygenation that take into account results from culture, mesocosm, and ocean process studies as well as autonomous observations and available global data compilations. Sensitivity studies with idealized scenarios will be performed to examine possible management ideas, such as ocean alkalization, artificial upwelling and 'blue carbon' measures to mediate anthropogenic pressures (contribution to DAM and HI-CAM).

In cooperation with ST6.1 and ST6.2, we will develop and improve marine biogeochemical models with specific emphasis on the role of ecology, adaptation, and evolution in marine biogeochemical cycles. To this end, optimality-based plankton models,[197] that explicitly account for organism behavior and flexible elemental stoichiometry and cell models[198] will be implemented and assessed in the framework of global models. We will employ our best calibrated models to improve our quantitative understanding of the ocean's carbon uptake under natural climate variability and expected future environmental change over the 21st century, employing IPCC scenarios for a 1.5°C, 2°C and 4°C warmer world relative to preindustrial time (link to T2). Application of these models to different climate states will allow us to address the possible contribution of cellular processes and ecological and evolutionary shifts to the climate sensitivity of the biological carbon pump. This work will contribute to the planning of a future CCA with T2, T4 and T5 that will study the dynamics of global carbon sinks and sources during the Anthropocene.

Deliverables (D) and Milestones (M)

- **D6.7 (2025):** Report on processes defining the efficiency of the biological carbon pump. **M6.7-1 (2023):** Identification of processes that modify particle dynamics in the mesopelagic ocean. **M6.7-2 (2024):** Integrate data sets of microbial and multicellular plankton ecology and pelagic biogeochemistry covering the seasonal and spatial variability of representative ecosystem types.
- **D6.8 (2025):** Report on carbon fluxes driven by the biological pump. **M6.8-1 (2022):** Ocean carbon dynamics and their drivers across subtropical gyres. **M6.8-2 (2022):** Insight into combined carbon and ox-

[195] *Schourup-Kristensen V, Wekerle C, Wolf-Gladrow DA, Völker C. 2018. Arctic Ocean biogeochemistry in the high resolution FESOM 1.4-REcoM2 model. Prog Oceanogr. 168:65-81.

[196] *Kriest I. 2017. Calibration of a simple and a complex model of global marine biogeochemistry. Biogeosciences. 14:4965–4984.

[197] *Pahlow M, Dietze H, Oschlies A. 2013. Optimality-based model of phytoplankton growth and diazotrophy. Mar Ecol Prog Ser. 489:1–16.
[197a] *Mengis N, Keller DP, Oschlies A. 2018. Systematic Correlation Matrix Evaluation (SCoMaE) – a bottom-up, science-led approach to identifying indicators. Earth System Dynamics. 9:15–31.

[198] *Holtz LM, Wolf-Gladrow D, Thoms S. 2017. Stable carbon isotope signals in particulate organic and inorganic carbon of coccolithophores – A numerical model study for *Emiliania huxleyi*. J Theor Biol. 420:117–127.

ygen dynamics in the ocean via Biogeochemical-Argo floats. **M6.8-3 (2024):** Regional budgets of benthic carbon fluxes.

- **D6.9 (2027):** Report on the CO_2 uptake in the ocean for a 1.5°C, 2°C and 4°C warmer world relative to preindustrial time. **M6.9-1 (2025):** Assessment of productivity dynamics in a changing ocean. **M6.9-2 (2025):** Assessment of organic carbon degradation dynamics.

Risks and Opportunities. Our understanding of the many chemical, biological and physical processes that constitute the biological carbon pump and their sensitivity and feedback potential to global change is still very limited. To, nevertheless, decode this complex system and reduce uncertainties with regard to the ocean's carbon sequestration from the atmosphere we will make full use of novel methodological approaches (e.g., 'omics', in situ sensing, deep-sea technologies, data science techniques) and the T6 framework that will for the first time enable us to fully integrate biological and biogeochemical process studies covering the entire ocean system. We will further benefit from the long-term research infrastructure developed and maintained by GEOMAR in Cape Verde and the strong collaborations within the Program (T2 and T4) and with our national and international partners.

Subtopic 6.4 Use and misuse of the ocean: Consequences for marine ecosystems

Erik Achterberg, GEOMAR; Gunnar Gerdts, AWI

Scope and challenges. Extraction of marine resources, intentional and unintentional waste disposal and emission of anthropogenic noise are exerting strong pressures on marine ecosystems (Fig. 6.6). ST6.4 will investigate how ecosystems respond to these human interventions and identify strategies to minimize their harmful environmental effects.

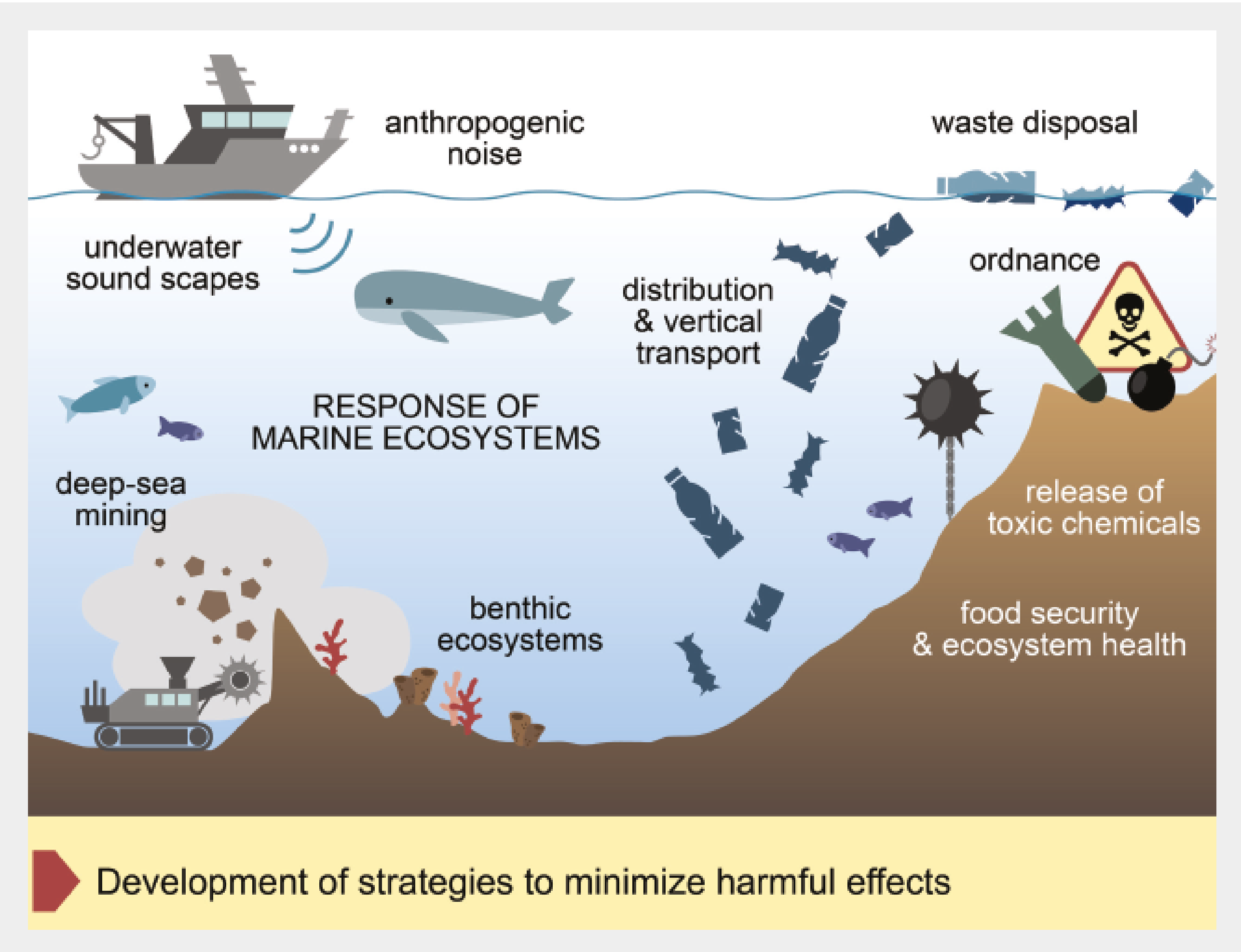


Fig. 6.6: Research objectives of ST6.4: Use and misuse of the ocean: Consequences for marine ecosystems.

Main objectives. We aim specifically to i) understand how the mining of mineral resources at the deep-sea floor (manganese nodules and massive sulfides) will affect benthic ecosystems and how the adverse effects of deep-sea mining can be minimized, ii) study the release of toxic chemicals from corroded ordnance disposed on the seafloor, the uptake of these chemicals by marine biota and the consequences for food security and ecosystem health, iii) investigate the distribution and vertical transport of plastic debris in the ocean and its interactions with the biological carbon pump and iv) understand how anthropogenic noise sources affect underwater ocean soundscapes and ecosystems. We aim for a comprehensive research strategy that provides standards for assessing human impacts on marine biodiversity, ecosystem function and services, and supports the design of management strategies for the protection of the marine environment.

Work program. Deep-sea mining. The last decade has seen a steady increase of interest in mining of deep-sea minerals, as documented by the growing number of exploration contracts issued by the International Seabed Authority (ISA) and the 'Blue Growth' strategy of the EU's Horizon2020 program funding marine mining technology projects. In this context, ISA is currently tasked with drafting of regulations for the exploitation of marine mineral resources. Hence, it is timely to investigate scientifically the expected environmental impacts of deep-sea mining.

Impacts from mining activities on the marine environment include the removal of surface sediments and benthic biota and the creation of a plume consisting of discharged mineral debris and/or suspended sediment that will also blanket untouched seafloor in the vicinity of the mined area. T6 scientists lead the JPI Oceans-funded project 'Mining Impact' that is focusing on impacts related to the harvesting of polymetallic nodules. Future projects will concentrate on the impacts of massive sulfide mining. The main scientific goals that ST6.4 will address are concerned with the quantification of the spatial and temporal spread of the suspended sediment plume generated by the mining operations and the assessment of impacts on ecosystem functions and biogeochemical processes. In practice, this means employing a combination of state-of-the-art technologies, such as in situ respiration chambers and microprofilers, genetic and metabolic analyses of microbial communities, biogeochemical modeling, quantitative image analysis of photomosaics and hydroacoustic mapping and monitoring. We will define threshold values for causing serious harm to the environment and its diverse habitats as well as novel spatial management concepts for minimizing the impact.

Ordnance disposal. Marine environments are contaminated globally with unexploded ordnance and munitions from intentional disposal, but their distribution and condition are not well known.[199] In addition to security risk of unintended explosions during construction operation and shipping route clearance, these munitions contain cytotoxic, genotoxic, and carcinogenic chemicals. The toxic chemicals are released from corroded ammunition and taken up by marine biota. High-resolution multibeam mapping, AUV-based optical ground-truthing, sub-bottom profiling and electromagnetic measurements allow discovery and detailed mapping of munition dumpsites and isolated ordnance while in situ chemical detection of dissolved munition compounds (including TNT, ADNT or RDX) and their breakdown products is applied to assess the environmental impact during long-term monitoring efforts as well as before and after munition clearance operations.

ST6.4 will undertake a combination of geophysical, chemical, ecological and physical oceanographic observations in coastal waters of the Baltic and North Sea in cooperation with T4 to assess the occurrence of munition and the spread of dissolved munition compounds related to daily and seasonal environmental fluctuations. To quantify the release rate of munition compounds in the field, we will employ benthic chamber experiments and photogrammetric time-lapse camera studies at the Kolberger Heide site in Kiel and Lübeck Bay in cooperation with European partners. These geophysical and chemical observations will be linked to munition compound concentrations in biota and ecotoxicological effects providing an assessment of the scale of contamination within flora and fauna.

[199] *Beck AJ, Gledhill M, Schlosser C, Stamer B, Böttcher C, Sternheim J, Greinert J, Achterberg EP. 2018. Spread, behavior, and ecosystem consequences of Conventional Munitions Compounds in Coastal Marine Waters. Front Mar Sci. 5:141.

Assessing and modeling the horizontal and vertical transport of plastic debris from continental coasts to the open ocean. The fluxes of plastic debris from terrestrial pollution sources across rivers, estuaries and shelf seas to the open ocean, including intermediate depo-centers along the transport pathways, are still poorly understood. Currently, 5-13 Mt of plastic debris are believed to enter the oceans from land every year, but only 1% of this has been found in the surface ocean.[200] The fate of the missing plastic has been explained by various processes, for instance by the negatively buoyant character of 50% of plastic debris which sinks to the seafloor where it accumulates over time.[201] Moreover, plastic particles become heavier over time as they are colonized by biota.[202] The resulting downward transport is facilitated by the biological carbon pump and constitutes the most efficient mechanism for plastic removal in the ocean. We will investigate both processes simultaneously, i.e., the biological carbon pump (ST6.3) and vertical plastic transport with related or even identical methods. A further fraction is deposited along coastlines[203] while an unknown proportion is taken up and transported by marine organisms. Little knowledge exists on trophic transfer and accumulation of plastic debris in marine food webs and on environmental impacts on sea ice, pelagic and deep-sea ecosystems. We will explore the consequences of plastic ingestion by fish and marine filter-feeding organisms and their potential effects upon organism function in collaboration with ST6.2 and Kiel University (CAU).

Our fieldwork will focus on the North Atlantic and Arctic regions. It will include the investigation of the downward transport facilitated by the biological pump and plastic pollution along the lateral transport pathway from selected river estuaries on both sides of the North Atlantic (e.g., Rhine, Elbe, Weser, St. Lawrence, Siberian rivers) across shelf sea areas (link to T4) towards the North Atlantic gyre and the Arctic.

Further sea-going expeditions and experiments (e.g., MOSAiC) will allow obtaining a mechanistic and quantitative understanding of biota-mediated transport and fragmentation processes, potential microbiological effects, and impacts on marine species. This work is amended by ocean observation studies conducted annually at the Cape Verde site and the LTER Hausgarten. Quantification of microplastics and plastic debris in all spheres in a standardized approach will allow us to identify hidden sinks.[204] Through repeated measurements, we will delineate temporal trends, which is crucial to assess the efficiency of mitigation measures including the EU Plastics Strategy. Project outcomes will be communicated effectively to the public by videos, blogs and articles and via the online portal LITTERBASE, which is run by the AWI since 2017. Scientific data compiled in LITTERBASE will also be used for scientific meta-analyses to deduce global patterns in the distribution of marine debris.

Effects of anthropogenic underwater noise. Anthropogenic underwater noise is prevalent throughout the world's oceans, and affects many aquatic species relying on sound for communication, orientation or foraging. Noise has been shown to interfere with critical life functions of aquatic organisms including fitness, and communication and may compromise habitat quality[205] and ecosystem functions. Here we will investigate how chronic noise affects underwater acoustic habitat quality by comparing two polar regions (Weddell Sea and Fram Strait) with strongly differing underwater noise regimes.[206]

ST6.4 will provide baseline information on the composition and noise budget of a virtually anthropogenic noise-free ocean region (Weddell Sea in the Atlantic sector of the Southern Ocean) – as a first-time reference of underwater natural soundscapes – and compare the noise budgets and biotic acoustic assemblage composition between this reference and affected soundscapes in the Arctic Fram Strait. Long-term passive acoustic observations in the Weddell Sea will constitute the basis for assessing the reference noise budget and

[200] van Sebille E, Wilcox C, Lebreton L, Maximenko N, Hardesty BD, van Franeker JA, Eriksen M, Siegel D, Galgani F, Law KL. 2015. A global inventory of small floating plastic debris. Environ Res Lett. 10(12):124006.

[201] *Tekman MB, Krumpen T, Bergmann M. 2017. Marine litter on deep Arctic seafloor continues to increase and spreads to the North at the HAUSGARTEN observatory. Deep-Sea Res I. 120:88–99.

[202] Ibid.

[203] *Bergmann M, Lutz B, Tekman MB, Gutow L. 2017. Citizen scientists reveal: Marine litter pollutes Arctic beaches and affects wild life. Mar Pollut Bull. 125(1-2):535–540.

[204] Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AWG, McGonigle D, Russell AE. 2004. Lost at Sea: Where Is All the Plastic?. Science. 304(5672):838.

[205] *Slabbekoorn H, Bouton N, van Opzeeland I, Coers A, ten Cate C, Popper AN. 2010. A noisy spring: the impact of globally rising underwater sound levels on fish. Trends Ecol Evol. 25(7):419–427.

[206] Jones KR, Klein CJ, Halpern BS, Venter O, Grantham H, Kuempel CD, Shumway N, Friedlander AM, Possingham HP, Watson JEM. 2018. The location and protection status of Earth's diminishing marine wilderness. Curr Biol. 28(15):2506–2512.

soundscape composition and dynamics. The Arctic Fram Strait is an ecologically similar oceanic realm, albeit seasonally dominated by anthropogenic noise (mostly airguns). This area will serve comparative purposes to evaluate the role of the major anthropogenic contributions in relation to the baseline information. Multi-year, multi-site passive acoustic data have been and continue to be collected by moored long-term underwater acoustic recorders, both from the Weddell Sea and the Fram Strait. Past[207] and ongoing work uses spectral analyses and diversity metrics as well as custom-developed metrics to calculate and assess noise budgets and automatically extract information from all significant underwater sound sources for data from both the reference as well as from the affected region. With this approach, ST6.4 will provide the first regional noise budgets for the Weddell Sea and Fram Strait areas comprising the temporal variation in the energetic contributions of all significant abiotic, biotic and anthropogenic underwater sound sources. The potential impacts of sound on polar organisms and ecosystems will be assessed in cooperation with ST6.1 and ST6.2.

Deliverables (D) and Milestones (M)

- **D6.14 (2022):** Development of threshold values for causing serious harm to the environment as well as novel spatial management concepts for minimizing the impact of deep-sea mining. **M6.14-1 (2021):** Collecting data and samples on environmental impacts from nodule habitats (e.g., SO268 and follow-up cruises).
- **D6.15 (2023):** Assessment of the occurrence of munition and spread of dissolved munition compounds. **M6.15-1 (2022):** Advance our understanding of munition in German marine waters by acoustic, magnetic and chemical sub-bottom measurements as well as repeated and targeted ground-truthing using AUVs with chemical, optical and magnetic sensors.
- **D6.16 (2027):** A numerical model of plastic transport rates in the North Atlantic that synthesizes the acquired information and assesses the consequences of plastic emission reduction programs. **M6.16-1 (2021):** Assessment of the horizontal and vertical distribution of plastic debris i) in the water column, ii) in seafloor sediments, and iii) coastal areas, as well as d) in pelagic and benthic fauna. **M6.16-2 (2025):** fieldwork in the Arctic using annual expeditions of RV Polarstern.
- **D6.17 (2026):** Regional noise budgets for the Weddell Sea and Fram Strait areas comprising the temporal variation in the energetic contributions of all significant abiotic, biotic and anthropogenic underwater sound sources. **M6.17-1 (2022):** Establishment of standards and baselines of ocean noise by international cooperation (IQOE).

Risks and Opportunities. Most of the research in ST6.4 is new and was so far supported mainly through third-party funded projects. With the new Program, this work is now anchored in a long-term strategy and will strongly contribute to the further development of scientific outcome and impact. Up to now, ST6.4 scientists have mainly studied the spread of pollutants in the marine environment as a contribution to national and international programs while the work on biological impacts was mostly covered by external partners, Employing the biological knowhow assembled in T6, we have now the opportunity to synoptically assess – for the first time – the effects of deep-sea mining, plastics, ordnance disposal and noise on marine organisms and ecosystems within in one Program, drawing also on concepts developed in T9 and the results of our international initiatives dedicated to specific marine pollution problems. Methods for plastic quantification in seawater, biota and marine sediments are not yet sufficiently developed. To meet this challenge, ST6.4 will take a leading role in setting up improved and novel technologies and strategies to standardize the quantification and identification of plastic debris, particularly nano-/micrometer-sized particles, in the marine environment (water, sediment, biota matrices). This effort will include improved methodologies for higher analytical sample throughput. All of the proposed ST6.4 work is essential in setting standards, methods and data flows nationally and internationally.

[207] *Menze S, Zitterbart DP, Van Opzeeland I, Boebel O. 2017. The influence of sea ice, wind speed and marine mammals on Southern Ocean ambient sound. Royal Soc Open Sci. 4(1):160370.

Infrastructures and resources. LKII infrastructure such as the RV Polarstern (to be replaced by Polarstern II), Heincke, Alkor and Poseidon (to be replaced by Meteor IV), and their seagoing equipment, as well as analytical and experimental facilities at GEOMAR and AWI (e.g., Kiel Marine Organism Culture Centre (KIMOCC) and Kiel Off-Shore Mesocosms for Ocean Simulations (KOSMOS)), long-term time series and the modular biogeochemical ocean observatories FRAM at LTER Hausgarten and CVOO/OSCM at Cape Verde build the backbone of the research in T6. Manned and unmanned submersibles (i.e., JAGO), autonomous observations systems (e.g., floats, gliders, drifters, voluntary observing ships), towed and stationary camera systems, benthic lander and crawler systems, and state-of-the-art sampling equipment (e.g., particle traps, TV-guided platforms, AUVs, large-volume pumps, neuston catamaran) in combination with analytical facilities (e.g., Raman and (µ-) Fourier-Transform infrared spectroscopy, modified microplastic sediment separator, Flow camera) are integral tools of T6 research that will be further developed in MOSES and ARCHES (together with ST2.4) and proposed to be augmented by new strategic investments in MUSE. Alongside with this, access to key AWI and GEOMAR infrastructure such as Scientific Computing, data repositories (PANGAEA) and information systems (FishBase; Sea Ice Portal, PANABIO/BENDER/WSMPA; image annotation BIIGLE) will be critical to accomplish the overall research objectives of T6. Modularized experimental structures will be established by joining forces between AWI and GEOMAR field sites.

E) Previous achievements of the contributing centers and infrastructures

Expertise and preliminary work. AWI and GEOMAR are international leaders in the field of marine biogeochemistry and in the study of ecological and evolutionary responses of marine life to climate change in regions from the tropic to the poles and from genes to ecosystems. Previous research focused on assessing the biological and biogeochemical consequences of ocean warming, acidification and deoxygenation and predicting the future consequences of climate change in terms of population shifts of key species and groups, which have a central position in the food web. Existing expertise from different biological and biogeochemical disciplines covers a wide range of scientific approaches: i) field work in open ocean, polar and deep-sea areas, including long-term ecological time series approaches and in situ experimentation, ii) investigation of organismal performance under precisely controlled physiological conditions, iii) study of population and community performance with molecular and genomic approaches, iv) investigation of combined nutrients, oxygen and carbon dynamics in the ocean, and more recently also plastic littering v) numerical modeling from organismal to ocean scale, and vi) remote sensing of phytoplankton diversity.

Uniqueness. For the first time, key biological and biogeochemical processes will be jointly studied over the entire ocean system from the equator to the poles by joining forces between GEOMAR and AWI/HIFMB researchers. T6 will conduct world-class research by investigating the diversity, adaptation and biogeochemical functioning of marine ecosystems in a changing ocean affected by global warming and other anthropogenic perturbations. It will provide and assess sustainable management options that are urgently needed to protect the oceans and will contribute significantly to UN SDG14 and the UN Decade of the Ocean (2021–2030).

F) Collaboration and transfer

Partners. T6 engages in a number of strategic national and international partnerships (Table 6.1) which are detailed below.

Table 6.1: T6 strategic national and international partnerships.

	Key partners	Joint efforts
Subtopic 6.1	Universities of Bremen, Oldenburg, Hamburg, and Rostock; Leibniz Institute for Baltic Sea Research (IOW); German Centre for Biodiversity Research (iDiv)	Marine biodiversity change and functional consequences
	Norwegian Polar Institute; Universities of Tromsø, Bergen, and Oslo (NO); Université Laval (CA); British Antarctic Survey (BAS) (UK); Polish Arctic Institute; CCAMLR; SCAR working group 'Integrating Climate and Ecosystem Dynamics' (ICED)	Arctic and Antarctic research
	Nelson Mandela University, Port Elizabeth (RSA); Danish Technical University Copenhagen; National Centre for Ecological Analysis and Synthesis, Santa Barbara (USA)	Marine ecosystem management and biodiversity conservation
Subtopic 6.2	University of Kiel	Metaorganisms, Kiel Evolution Centre, bioinformatics network
	DFG-Competence Centre Genomic Analysis; Universities of Bremen and Oldenburg; Jacobs University; MARUM; ZMT; Max Planck Institutes Bremen and Plön	Organismal adaptation
	Norwegian Polar Institute; Universities of Tromsø, Bergen, and Oslo (NO); Université Laval (CA), BAS (UK); Ocean Frontier Institute Canada; Dalhousie University (CA); Australian Antarctic Division	Arctic and Antarctic research; HOSST Transatlantic Research School
Subtopic 6.3	IOW; Universities of Hamburg and Bremen; MARUM	Marine carbon cycling; Excellence Cluster with research on the biological carbon pump
	National Oceanographic Institutes in the UK (NOC) and France (IFREMER); Laboratoire d'Océanographie de Villefranche-sur-Mer (FR); University of Las Palmas de Canarias and Plataforma Oceánica de Canarias (ES); University of Southern Denmark	Biological carbon pump at continental margins and low latitudes
	Norwegian Polar Institute; University of Tromsø (NO); British Antarctic Survey (UK)	Polar research
	Instituto del Mar del Perú (PE)	Ecology and biogeochemistry in coastal upwelling zones
	Instituto Nacional de Desenvolvimento das Pescas (Cape Verde) and other WASCAL African member countries	Physical, chemical, biological oceanography, atmospheric sciences, ocean observation technology, regional academic education & capacity building

Table 6.1: Cont.

	Key partners	Joint efforts
Subtopic 6.4	IOW; MELUND SH; Fraunhofer ICT; EGEOS-GmbH; Universities of Kiel and Bremen; BGR; Senckenberg	Mining impacts, ordnance disposal
	UFZ; IOW; University of Bayreuth; ICBM Oldenburg; Thünen Institute of Fisheries Ecology	Assessment and modeling of horizontal and vertical transport of plastic debris
	JPIO consortium 'Environmental Impacts and Risks of Deep-Sea Mining' (various European partners); ISA	Mining impacts
	NATO; VLIZ (BE); Boskalis (NL); US EPA (USA); G-Tech (BE)	Ordnance Disposal
	Partners from Scandinavia, Italy, USA, and Russia	Assessment and modeling of horizontal and vertical transport of plastic debris
	NOAA; IQOE	Underwater noise

Positioning of the Topic in international research. Many of the researchers involved in T6 have been and are leading large-scale European Research projects, including ERC projects. T6 directly provides critical knowledge to IPCC and IPBES assessments and to guide sustainable management of marine resources under UN SDG 14. It is also one of the key contributions of German research to the UN Decade of the Ocean (2021–2030).

Cross-Topic and Cross-Program-Activities. T6 engages in the Cross-Topic Activities (CTAs) MOSES, ESM and Digital Earth, in the Cooperations across Research Fields (CARFs) HI-CAM and ARCHES and the Alliance DAM. T6 contributes significant personal, resources and expertise to these activities and benefits by applying the robotic ocean observing systems developed in MOSES and ARCHES, the data science approaches provided by Digital Earth and the ocean models developed in ESM. Moreover, T6 scientists are currently setting up two major programs in DAM and HI-CAM that will investigate the carbon uptake in the ocean and its role in climate change mitigation. T6 also participates in the Helmholtz Incubator 'Information and Data Science', in particular to the Metadata Center and RF E&E Metadata Hub (see Ch. 1), and to the Helmholtz School for Marine Data Science (MarDATA). MarDATA will train Ph.D. students in merged themes of data and computational sciences with marine sciences. The involved disciplines include computer sciences, bioinformatics and mathematics (with modeling, supercomputing, robotics, machine-learning) and will be embedded into ocean sciences, resulting in a novel understanding of 'marine data science'. T6 scientists will co-supervise Ph.D. researchers working on T6 themes related to bioinformatics, image processing, robotic applications and data mining and will greatly benefit from the data science expertise provided by co-supervisors from the Universities of Kiel and Bremen.

Together with T1, T2, T3, and T5 we are developing a concept for a new CCA that will address extreme events in a changing world from a biological perspective. Extreme events pose a potential threat to societies, their assets and the environment. Owing to the properties of extreme value distributions, weather and climate extremes are expected to increase disproportionally in the future, along with further upward shifts, e.g., in mean temperature, ocean acidification, or oxygen deficiency In the context of environmental changes and marine life it is largely unknown how resilient species are, how communities will react, how resilient they are, and whether they will recover. We will explore how species and communities respond to e.g., sea surface temperature extremes (marine heatwaves) and related mass coral bleaching and macroalgae die-offs. We will also support T2 in building a new CCA on thresholds of the Earth system with regard to the dynamics of carbon sources and sinks in past, present and future warming states, in which the ocean's biological carbon pump plays an important role.

Transfer and contribution to SynCom. Knowledge transfer and dissemination occur along several channels, such as i) advising the IPCC especially in the framework of the 'Special Report on the Ocean and Cryosphere in a Changing Climate' (SROCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) on marine biodiversity, the Global Carbon Project, and the International Seabed Authority (ISA) on sustainable use of deep-sea resources, ii) transferring knowledge to policy makers as well as to medical and biotechnology disciplines for specific applications, iii) dissemination of information and engaging in dialogue with the public by reports[208] and support of publicly available databases (e.g., FishBase, LITTERBASE), iv) Massive Open Online Courses (MOOCs), and v) citizen science formats. GEOMAR is also closely affiliated with the local Ocean Solutions Hub at Kiel University. T6 is supported by knowledge transfer offices at the participating centers, and will contribute to SynCom by providing integrated assessment reports on the response of marine ecosystems to human impacts and on management options that can be applied to preserve biodiversity and ecosystem functioning under global change and mitigate harmful effects of deep-sea mining and other human interventions.

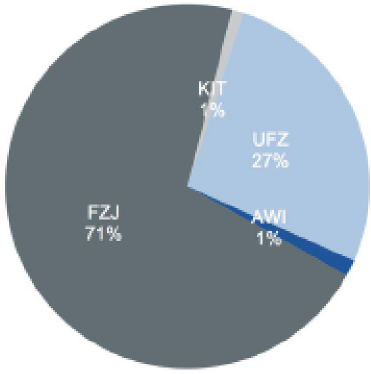
Executive Summary

- T6 integrates ecological, evolutionary and biogeochemical approaches to understand, quantify, and forecast the responses of marine life to climate change and other human pressures. It will contribute to the Earth system research of the Program by quantifying the CO_2 uptake in the global ocean, by achieving an unprecedented level of interaction between biogeochemical and biological approaches, and by studying the entire ocean system from the equator to the poles.
- T6 contributes to the scientific objectives 2, 3, 6, 7, 8, 9 and 10 of the Program by developing management options to protect the marine ecosystem and minimize the impacts of climate change, resource extraction and pollution on marine ecosystems, biodiversity and ecosystem services.
- T6 will include key contributions of German research to the UN Decade of the Ocean Science for Sustainable Development 2021–2030 and to UN SDG 14 'Life Under Water' as well as to a variety of assessments on ocean and biodiversity states.

[208] See https://worldoceanreview.com.

Topic 7: Towards a Sustainable Bioeconomy – Resources, Utilization, Engineering and AgroEcosystems

Spokesperson: Ulrich Schurr, FZJ



The mission of Topic 7 is to contribute to a sustainable bioeconomy that provides food and renewable resources for industry to a growing and demanding human population while reducing the environmental footprint and supporting a growing circular economy. T7 aims to improve and make efficient use of biological and environmental resources for sustainable production, contributes engineering of renewable carbon sources and chemicals to innovative products, and integrates production into the sustainable use of agro-biogeosystems.

A) Scope and challenge of the Topic

Research subject. Producing food and feed, materials, chemicals and energy carriers require the use of natural resources. However, current practices consume resources much faster than they can be replenished by natural cycles. Therefore, a central challenge in the management of the Earth system is to develop a sustainable economy, which fulfills human needs, but does not overexploit the resources. This is a major task with the world population expected to be close to ten billion in 2050. The linear approach of today´s economy with massive overconsumption of natural resources and goods based on excessive use of fossil resources is not sustainable. In contrast, a sustainable economy needs to provide stewardship to natural resources and must integrate human consumption into the circular economy. The target is a sustainable supply of ample and healthy food and feed, sufficient and innovative materials and chemicals as well as renewable energy. At the same time, we need to reduce the negative impact on vital functions of (eco-) systems and provide stewardship to precious resources like atmosphere, land, water, nutrients as well as to marine, coastal and urban environments and biodiversity.

Utilizing knowledge about biological systems will be key to deliver towards i) improving production for food and feed, chemicals, materials and energy with respect to amount, quality and footprint, ii) increasing the efficiency of the use of natural resources, while decreasing overconsumption, and iii) making the global economy more sustainable by application of biological concepts (or principles) in economic and technical environments.

Explanation and justification of research. The United Nations has encoded major challenges into 17 Sustainable Development Goals (SDGs), which provide the basis of the research in Topic 7 (T7): sustainable food/feed systems will be a key deliverable for a growing population with changing food preferences (SDG 2: Zero Hunger, SDG 3: Good Health). Since agriculture is the major consumer of fresh water globally, a water-efficient agriculture with environmentally-safe use of chemicals, fertilizers and manure, will be key to protect the quality and quantity of water (SDG 6) and of soil functions (SDG 15). Novel technologies and more efficient, sustainable, and climate-friendly production of chemicals and materials and responsible consumption (SDG 12) are crucial for a circular economy (SDG 9) and to sustain cities and communities (SDG 11). Translating our results into action integrated in Earth system management delivers to climate action (SDG 13). Research in T7 addresses issues related to the special report of the IPCC on climate and land (SRCCL 2019) with respect to sustainable production and consumption.

Sustainable and efficient use of resources and stewardship to ecosystems requires to obtain and apply deeper knowledge about biological systems. Novel routes of conversion and use of natural resources as part of a circular (bio-) economy require state-of-the-art research and development of technologies as well as embedding knowledge about production, resources and impact into the Earth system management. The capability of T7 to integrate biological knowledge with engineering and technological developments is a point of uniqueness within the international bioeconomy research community. This includes the world-leading position in overcoming key bottlenecks in characterizing biological resources by phenotyping and bioinformatics as well as the intimate linkage of feedstock production and the development of conversion and use systems. Finally, agroecosystems provide the interface between production systems, the impact on the Earth system, as well as the feedback of the environment on production. Here, our target goes beyond the description and observation of 'issues', but delivering practical solutions to farmers and regulatory bodies based on sound analysis, empirical and model-based testing of alternative scenarios. An overall strength of the Topic is the tight integration of important aspects of the bioeconomy value chain and the opportunity to analyze risks and benefits in a systemic manner in concert with other Topics.

Research in T7 requires efficient interfaces with dynamically developing themes in energy and chemistry (renewable resources and distributed processing) and health (nutrition and disease), and with the digital sector (digital bioeconomy). The rapid developments in digital technologies allow quantitative understanding of systems as well as generating new business cases in bioeconomy with high implementation likelihood. Thus, providing solutions includes active technology and knowledge transfer. This is an evident strength of this Topic building on many long-term partnerships with industry, breeders, and farmers as well as with politics and civil society. This includes existing cooperation with breeders, agricultural industry, food industry, the biotechnology sector, chemical industry, manufacturing and the IT sectors.

Strategic guidelines (FoPoZ). Research in T7 addresses major policy goals of the German federal and state governments (FoPoZ), which themselves are aligned with European and global bioeconomy strategies. With the approach to support sustainable use of natural resources and provide stewardship to the Earth system, the Topic is at the forefront of international developments for sustainable bioeconomy. Bioeconomy will be embedded into the concepts of circular economy targets towards developing sustainable solutions. For analysis of impact of production and integrated solutions, we will cooperate with T5, T8 and T9 in socio-economic analysis and scenario evaluation. T7 develops technologies in phenotyping, bioinformatics, and biotechnology and engineering, addresses processes to fractionate biomass and provide food, raw materials, higher-value products or energy and on integrating biological systems in technical environments to utilize their potential to design efficient production systems and products with low footprint, improved performance and novel properties. This unique combination of technical and biological expertise targets for sustainable solutions, new economic opportunities and processes that respect the capacity of terrestrial and marine compartments.

Aspects of urban bioeconomy will be addressed within the CARF Resilient Urban Spaces and include, for example, production of biomass in urban regions, use of crop residues for materials and chemicals, as well as wastewater technologies. We will also address food security and food waste in urban areas. The rural-urban nexus is addressed directly in the bioeconomy model region BioRevier Rhineland, developed against the background of the closing of lignite mining in that region. The region has decided to become a model region for bioeconomy based on its unique natural, economic, social and scientific competences. On the international level, T7 focuses on implementation of bioeconomy solutions at hotspots of economic and population development. Based on long-term partnerships (funded e.g., by Bioeconomy International (BMBF), Gates Foundation and funds from the regions), we focus on Thailand as a reliable entry point to the ASEAN region (joint Lab FZJ-NSTDA since 2019), Brazil (joint lab FZJ-EMBRAPA since 2012) and the extended network with WASCAL/ SASSCAL partners in Africa.

Function and contribution of the Topic within the Program. Sustainable production and use of biological resources must be an essential element of Earth System Research. T7 delivers a unique perspective to develop sustainable solutions with economic, social, and ecological dimensions in concert with the other Topics of the Program. Therefore, the integration of T7 into the Program provides the unique opportunity to (pro)actively address options for and conflicts in the use of land and biological resources. T7 generates knowledge about biological resources and their utilization, conversion and environmental impact to improve provision of bio-based resources and products to industry and society, while targeting the necessary balance between use and stewardship of biological and biogeochemical resources. It is a major step and achievement to integrate bio-economy and circular economy research into the RF E&E in PoF IV. However, this also provides challenges for T7 as well as the Program as a whole: practical integration of research in this Topic is presently less intensive than between other Topics. This is due to the fact that these initiatives were launched within the RF E&E during PoF III, when most of the participants of T7 were included in RF Key Technologies and RF Energy. In order to valorize the unique opportunity of embedding production systems into Earth System Research, interactions have already been deepened during the Program development and will be further intensified.

Research in T7 will integrate with non-bio-based renewable solutions (e.g., renewable energy, CARF with RF Energy), with improvements in the health system (e.g., disease prevention by healthy food and feed, T9 and CARF with RF Health) as well as with ecological research and social and economic innovation (e.g., with T5, T9). Collaboration with T1 will focus on lowering the impact of agricultural production to GHG emissions as well as in determining scenarios of future weather conditions and their impact on crop production. Bioeconomy will also address aspects in urban spaces (CARF Resilient Urban Spaces). Production systems are also the link to T4, where – especially in deltas of large rivers – agricultural production contributes significantly to the drivers of developments in coastal regions. In addition, links with coastal (T4) and marine systems (T6) exist, wherever production takes place in aquatic environments.

Highlights. A particular strength of T7 is its expertise in the quantification of bioeconomy systems. This provides the basis to predict and optimize the performance in all three domains of the Topic. Research in T7 utilizes all dimensions of digital bioeconomy: experimentation, automation, digitalization, data science and modeling in all Subtopics. Researchers of T7 are at the forefront of developing non-invasive technologies, image analysis and automation including phenotyping and bioinformatics of plant and microbes, prediction models for structure and function in plants, microbes, bioreactors, and biorefineries as well as in agroecosystems. We will integrate most advanced technologies in digitization and IT into bioeconomy research based on intimate integration with the RF Information, the Helmholtz Digitalization Strategy, as well as the Excellence Clusters PhenoRob[209] and CEPLAS[210].

[209] PhenoRob is an Excellence Cluster on AgriRobotics jointly run by University of Bonn and Forschungszentrum Jülich.

[210] CEPLAS is an Excellence Cluster on improvement of plants and plant-microbe interaction jointly run by University of Düsseldorf, University of Cologne, MPI Plant Breeding and Forschungszentrum Jülich.

B) Main research and structural objectives

Research Objectives.

- **Objective 1:** Establish responsible use of biological and natural resources on land and in the aquaculture as an essential element towards a sustainable future of human activities on our planet.
- **Objective 2:** Establish bioeconomy solutions within a hybrid circular economy targeting for sustainable solutions.
- **Objective 3:** Contribute to a future-proof, high-quality food system integrating health-promoting and circularity principles.
- **Objective 4:** Develop and innovate products replacing fossil resources in chemical, materials and energy sectors.
- **Objective 5:** Develop and utilize digital techniques in bioeconomy research.
- **Objective 6:** Characterize microbial and plant biodiversity and make it available for use in breeding, industrial biotechnology (novel products), and environmental engineering.
- **Objective 7:** Regionalize bioeconomy to implement regional solutions that contribute to global sustainable development goals (SDGs).

Structural Objectives.

- **Objective 8:** Establish leading infrastructures (ESFRI) for digital bioeconomy in plant phenotyping (EMPHASIS) and Earth system monitoring (LTER) for bioeconomy research.
- **Objective 9:** Establish and support the development of model regions for sustainable bioeconomy in Germany and internationally in Africa, SE-Asia and Latin America.
- **Objective 10:** Develop efficient transfer of knowledge, technology and concepts to industries, politics and society.

C) Structure of the Topic and motivation of Subtopics

Introduction of Subtopics. ST7.1 characterizes and develops land-based and aquatic crops, microbes and microbial functions in ecosystems as the basis for sustainable production of food/feed and non-food applications. It provides the knowledge basis on essential biological and environmental resources of a sustainable bioeconomy. ST7.2 addresses the conversion of renewable carbon sources with respect to use in food and non-food applications and the establishment of engineered ecosystem functions to reduce chemical footprint in agro-biogeosystems. ST7.3 studies mechanisms of environmental controls, feedbacks and impacts of agro-biogeosystems as a basis for sustainable production systems.

Contributions of the Centers to the Topic. T7 includes all bioeconomy activities of **FZJ**, where bioeconomy is one of three strategic pillars. Bioeconomy research at FZJ closely interacts with the RF Energy and the RF Information, i) in integration of energy systems with biotechnology, plant and bio-geosciences, ii) in digital bioeconomy including data sciences, bioinformatics, modeling and supercomputing as well as iii) in structural biology and biophysics. Specific contributions to ST7.1 and ST7.2 include crop and microbial physiology, phenotyping, systems biology, bioinformatics, plant and microbial biotechnology, as well as conversion processes in biorefineries. Remote sensing, agroecosystem experiments and modeling are developed and utilized for breeding and crop management (ST7.1, ST7.3). **UFZ**'s research in STs 7.1 and 7.2 contributes an integrated approach covering control of the fate of chemicals in the environment, sustainable biotechnology and bioeconomy by providing disciplinary expertise in environmental microbiology, chemistry, (electro- and photo-) biotechnology as well as in isotope biochemistry. This provides strong links to (eco-)toxicological research in T9 and water, soil and social sciences in T5. **AWI** participates with research utilizing biological models to develop bionic lightweight engineering and developing sustainable aquaculture to ST7.1. **KIT** develops technological solutions for water provision, separation and degradation of pollutants, from material through multiscale models to processes in ST7.2.

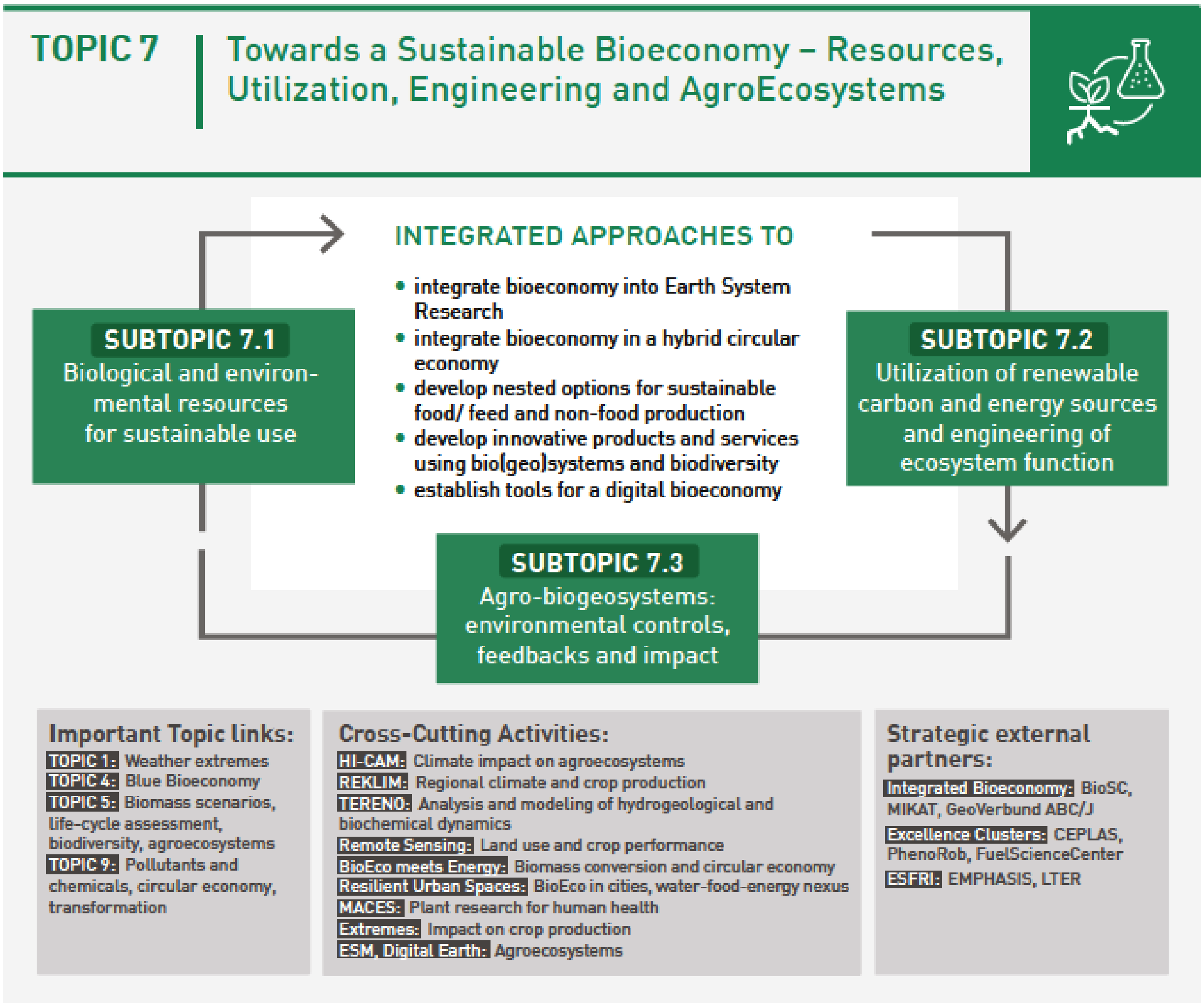


Fig. 7.1: Graphical scheme of Topic 7.

D) Subtopics

Subtopic 7.1 Biological and environmental resources for sustainable use

Ulrich Schurr, FZJ; Michael Bott, FZJ

Scope and challenges. Plants, microbes, enzymes, aquaculture organisms and their ecosystems represent major targets for production systems and for maintaining biological resources. ST7.1 will expand and improve the fundamental knowledge on these resources as basis for bioeconomy value chains/networks and on ecosystem functions, including the capabilities of microbial systems to break down organic chemicals under field conditions. It will contribute novel technologies and methods to improve plant breeding, microbial strain development and aquaculture systems. Highlights are the unique competence in ST7.1 to gain quantitative information on dynamic performance of organisms under production conditions. We develop and use a unique portfolio of 'omics' technologies, (bio)informatics, bioengineering, non-invasive phenotyping technologies, and quantitative remote sensing focusing on digital bioeconomy approaches.

Main objectives.

- Develop deep understanding of crop functioning under dynamic conditions of global change and for development of resource-efficient production systems.
- Establish biological fundamentals and tools for the design and utilization of microbial resources for industrial biotechnology and environmental technology.

- Characterize microbial functions in natural ecosystems for sustainable use of chemicals.
- Develop sustainable aquatic food production systems.

Work program.

Resource-efficient bio-based systems: crops and cropping systems with high resource use efficiency, resilient to climate change, and minimizing environmental impact.

Challenge: Plants and plant production are central elements of production for bioeconomy use. Breeding has significant impact on economy, ecology and society[211]: e.g., the increase in yield due to breeding is equivalent to 22 million tons of wheat each year and a reduction of CO_2 emissions by 160 million tons/year. However, the urgency to improve yield and to lower the environmental footprint increases, as stated by the Food and Agriculture Organization of the United Nations (FAO). We aim i) to improve agricultural production systems for less input at increased yield and ii) to provide biomass with enhanced quality and composition for food, feed, renewable biomass resources and bioenergy. Plants are essential iii) to close (nutrient) cycles. We will also iv) improve technical systems by applying biological, evolutionary-optimized structures, materials and processes.

Approach: To improve and accelerate plant breeding towards more efficient crops while maintaining biodiversity and ecosystem stability, phenotyping and genotyping technologies and their integration by bioinformatics need to be developed beyond state-of-the-art. Four goals are central to ST7.1: i) discover novel plant ideotypes and crop stand performance that increase productivity per unit area and efficiency of use of water, nutrients etc., ii) adapt quality of biomass to downstream needs for food/feed and non-food applications, iii) analyze organismal traits and systematically transfer the findings into breeding and iv) characterize crop genetic resources to accelerate breeding. Novel plant traits will be identified, based on excellent physiological competences, unique non-invasive technologies, deep understanding of nutrient and water relations at the crop and canopy level. We will build on our unique expertise in structural and functional analysis for optimization photosynthesis and carbon partitioning at the crop and stand level at future climate conditions (e.g., BREED-FACE), and will use remote sensing at regional and global scale. Improving crop composition comprises secondary metabolites and cell walls leading to alternative biomass resources. This includes development of integrated crop systems producing on marginal lands (perennials) and of microalgae-based systems for biomass production and for closing nutrient cycles. We will develop deep and integrated understanding of genotype-phenotype-environment based on the combination of state-of-the-art phenotyping, genotyping and bioinformatics.

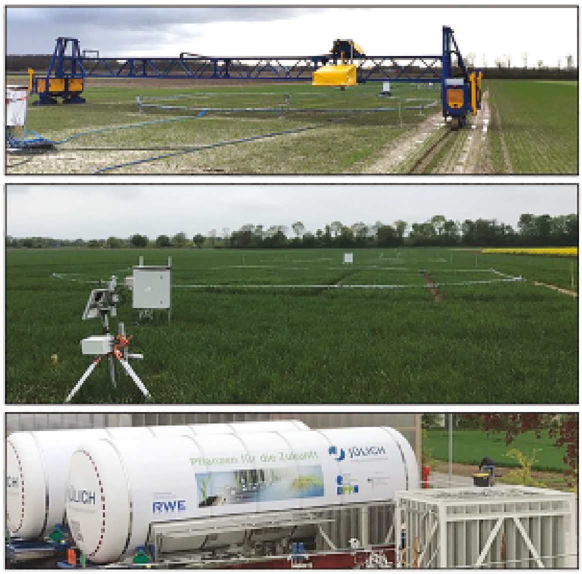


Fig. 7.2: Breed-FACE at Campus Kleinaltendorf. This system allows analyzing the performance of crop plants (specifically focusing on breeding) at future CO_2 conditions in the field. The unique experimental facility is set up with most modern field phenotyping.

[211] Noleppa, S. 2016. The economic, social and environmental value of plant breeding in the European Union. An ex post evaluation and ex ante assessment. See http://www.plantetp.org/system/files/publications/files/hffa_research_paper_plant_breeding_eu.pdf.

Root systems are essential to acquire belowground resources. We will improve their architecture and function including crop-crop and crop-microbiome interactions for improved water, nutrient and energy efficiency. We are uniquely positioned to discover how root systems function in association with the soil using modern tomographic methods. We will build on our research pipeline, integrating architectural/functional analysis of roots and shoots, plant analysis of genetic determinants and environmental plasticity, analysis of root performance in various field scenarios, and implementation of physiological knowledge into (pre)breeding designs. Experimental results will be included in functional structural plant models and agro-ecosystem models with ST7.3.

We will continue to explore the diversity of seed bank material to identify options for improved crop performance in collaboration with partners from major national and international seed banks (e.g., Global Crop Diversity Trust, Gates Foundation and CGIAR). This will be based on detailed and high-throughput seed phenotyping technologies based on robotics, automation and machine learning. Alternative biomass resources, biomass quality and plant-based products will be developed for improved food/feed quality as well as for utilization in biorefineries. Plants provide lignocellulose as a 'bulk' product, and, in addition, produce valuable secondary metabolites. The latter provide health bestowing effects and taste, and can be used as colorants or odorants etc. Thus, we will study cell wall and secondary metabolite composition, biosynthesis, and impact of environmental conditions as well as a basis for the use in microbial biotechnology (ST7.2). We develop algae production systems as a source of biomass for biorefineries, to reduce nutrient leaching and as a novel fertilizer resource. In addition, perennial plants offer new opportunities for crop production especially on marginal lands, where they also have ecological benefit (biodiversity) and are used for closing the nutrient cycle with biorefineries.

With respect to technologies, phenotyping is a major bottleneck for progress in plant sciences and breeding. Hence, we will continue to extend, apply and provide access to our unique portfolio of phenotyping infrastructure in controlled and field conditions. We will integrate the novel technologies with ontologies and data management systems from (bio)informatics. Anatomical and morphological plant traits as well as water flux (NMR), carbon transport, and allocation of photoassimilates (PET) will be studied in vivo. We also will realize devices and screening concepts (e.g., cell phone-based) that allow broad access to modern phenotyping concepts. Marginal Field Labs will be established as a unique field infrastructure within the BioeconomyREVIER Rhineland: we will utilize options due to the end of lignite mining to establish a large-scale experimental facility to test crops, biologicals and soil improvement products in diverse marginality of soils and include this facility into the European research infrastructure EMPHASIS (ESFRI). We will promote the wide adoption of best practices and standard procedures for plant phenotyping with breeders and develop even stronger links to digital agriculture and agro-robotics (PhenoRob).

Bioinformatics and big data application in plant and agricultural sciences will combine 'omics' databases, knowledge extraction and management, with AR/VR visualization support systems. We build and extend our bioinformatics platforms by providing databases and tools for valorization of 'omics' technologies. A special focus will be on network reconstruction and deep learning approaches integrating knowledge on algorithms and analysis of biochemical pathways linked to environmental cues, quality and yield of biomass. The focus is on metabolomics and transcriptomic data sets, but as proteomics matures, more and more data is integrated. We utilize state-of-the-art sequencing technologies (e.g., nanopore sequencing) to analyze the genetic background of key traits in crops and wild relatives to identify mechanisms established during domestication as well as future options to improve crops. In addition, we integrate phenotypic data with genetics and 'omics' and data from remote sensing devices analyzing agronomic performance.

Analysis of structures and functions of plants and marine organisms will also be used to develop novel bio-inspired approaches for the development of structurally-optimized technical structures. We will analyze natural structures and functions and apply biophysical principles and generative design software for i) resource-efficient multifunctional light-weight structures optimized for robustness, permeability and vibration properties, ii) nanocomposites in complex lightweight geometries and material substitution (e.g., biodegradable plastics), and iii) the development of morphogenetic algorithms for sustainable product development.

Biological fundamentals and tools for application of microbial resources in industrial biotechnology.

Challenge: Microbes or microbial communities in technical environments provide a huge potential to establish novel production processes in the food/feed, materials, energy, chemicals, and pharmaceutical industry. Biocatalysts enable access to products that cannot be efficiently provided by chemical synthesis. Currently, only a small fraction of the available microbiological diversity is used. Compared to human-made chemical plants, the use of microbes or microbial communities as 'cell factories' catalyzing natural or non-natural biochemical processes in technical environments is much more challenging. These systems have been shaped by evolution over billions of years in different environments, and the function of many components and numerous cellular activities and molecular mechanisms are either unknown or not well understood.

Approach: Improve biological knowledge and novel tools required for efficient and fast development of microbial producer strains or communities and of production processes (ST7.2).

A systemic analysis of microbial producer strains with proven application potential will be performed with the aim to obtain detailed molecular understanding of the metabolic and regulatory networks. A specific long-term aim will be a comprehensive analysis of the transcriptional network in 'Corynebacterium glutamicum' as basis for metabolic engineering and the construction of new biosensors for high-throughput screening and single cell-based live-cell imaging (Fig. 7.3). Novel genome-wide studies have disclosed that the current view on transcriptional regulation is way too simple and does not reflect dynamics and network interference. Genome-wide studies will be employed to obtain a more realistic view. The data obtained will be used to build computational models on the scale of biochemical and regulatory networks, whole cells, and processes as a scaffold for data integration, systems analysis and design (see below).

We will search for and characterize additional microorganisms and microbial communities with favorable properties that can serve as future industrial cell factories. Examples are solvent-tolerant *Pseudomonas* strains, acid-tolerant *Ustilago* strains, fast-growing *Vibrio natriegens*, CO_2-fixing phototrophic bacteria, acetic acid bacteria for oxidative biotransformation, and microbes with specific capabilities in anaerobic reductive metabolism. Besides studies on single microbes (including genome-reduced strains), synthetic microbial communities will be explored. Based on the individual metabolic capabilities of different microbes, their co-cultivation offers new possibilities both regarding the carbon sources that can be utilized and the products that can be synthesized.

We aim at microbial resource mining by analyzing the genetic and biochemical potential of natural microbes and microbial communities including phages present in various terrestrial and marine habitats. The communities will be screened for novel enzymatic functions and pathways which can be exploited for biotechnological processes or environmental contaminant degradation (ST7.2). We will also investigate metal-containing redox enzymes to be used for engineered electron transport processes. Another aspect in the context of using biodiversity will be studies on the untapped potential of phages in biotechnology, e.g., as source of new genetic tools, as modulators of metabolism or in the context of plant health.

The studies will be complemented by the development and application of advanced analytical tools for microbial (community) genotyping and phenotyping. This includes the establishment of advanced 'omics' methods based on DNA-Seq, RNA-Seq, ChIP-Seq, proteomics, fluxomics, and isotope-based methods. New database

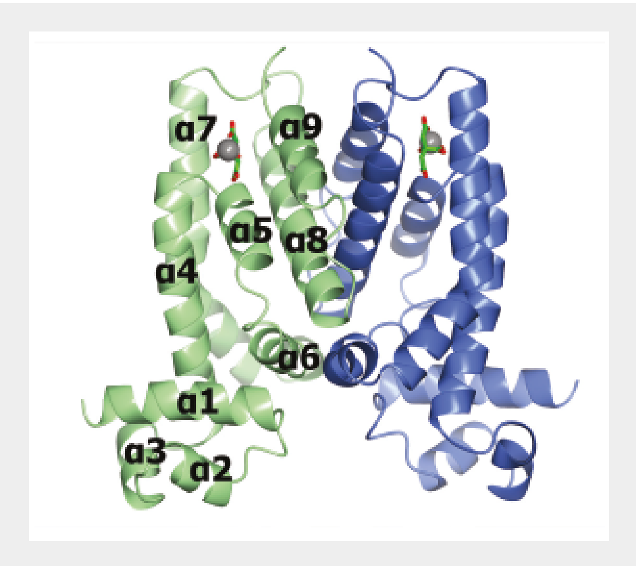


Fig. 7.3: Structure of a transcriptional regulator functioning as biosensor.

and bioinformatics tools will be implemented to handle, evaluate, and visualize these data. Additionally, novel bioinformatics, model-based and data science tools for optimal experimental design, raw data processing and integrated evaluation of the different 'omics' data will be required. Miniaturized and automated cultivation systems coupled to a variety of analytical devices and intelligent experimental control algorithms will be developed to enable high-throughput microbial phenotyping.

Reading out biologically relevant information and gaining control over metabolic processes on the single cell level is important for implementing novel high-throughput screening tools and for analyzing microbial population heterogeneity. We will design genetically encoded biosensors allowing visualization in single cells of a variety of parameters such as metabolite levels or stress responses. Biosensors based on transcriptional regulators (above) enable high-throughput screening of cell libraries by fluorescence-activated cell sorting (FACS). This allows identifying novel targets for strain and enzyme engineering that cannot be predicted rationally. FRET-based biosensors will be implemented for real-time monitoring in microtiter plate-based cultivation devices of cellular parameters such as sugar consumption. Optogenetic tools based on genetically encoded light sensors or photocaged inducers will be developed in order to temporally and spatially control gene expression.

Heterogeneity and interaction of microbial cells in a production bioreactor is still one of the white spots in industrial biotechnology. Custom-made microfluidic cultivation devices (cooperation with RF Information) linked to live cell microscopy will be developed. They enable the study of biological phenomena at the single cell level under highly defined environmental conditions. Combining this technology with genetically encoded biosensors giving a fluorescent readout allows almost real-time observation processes such as the emergence of population heterogeneity. A major challenge in the application of microfluidic cultivation systems coupled to live cell microscopy is automated high-speed image processing and evaluation, for which state-of-the-art data science tools have to be implemented. Complementary to imaging, microfluidics-coupled mass spectrometry (MS) will be developed as a label-free analysis tool for determining uptake and production rates, as well as yield coefficients at the single cell level or with microcolonies. This technology will allow us to link environmental conditions, heterogeneity, and productivity and to unravel novel targets for strain and process engineering.

Microbial functions in natural ecosystems for sustainable use of chemicals.

Challenge: Current use of anthropogenic organic chemicals is not sustainable, meaning that their imbalanced emission and environmental degradation leads to apparent persistence and resulting effects on respective ecosystems. The apparent persistence requires both tiered management strategies to reduce the environmental burden and adjusted research efforts to derive knowledge-driven management options to reduce environmental and human exposure (T9).

Approach: The focus is on understanding and predicting chemicals' fate and persistence from a (microbial) ecosystem perspective. We will develop tools to understand and predict degradation of chemicals from the nanometer up to large (meter to landscape) scale by integrating chemical and environmental properties. This will provide input to predictive modeling and risk assessment of chemicals, support chemical regulation and sustainable use, and improve treatment management options for unwanted chemicals and waste (e.g., plastic).

Mechanistic understanding of the effectiveness, dynamics, and functional stability of natural (and engineered) microbial ecosystems to degrade chemicals is of importance and needs to be derived from ecological principles at diverse spatial scales. In-depth knowledge about the microscale processes will support the characterization and prediction of the effectiveness, stability and functional capacity of (natural and engineered) ecosystems to convert/degrade chemicals and waste materials at macro spatial scales up to the landscape level (T5). Understanding of hotspots and drivers of microbial activity (e.g., the rhizo- and mycosphere) will be paramount for the turnover of chemicals in the environment and their transformation products. Experimental and modeling studies will tackle the functional stability of the required complex microbial ecosystems. We will investigate factors controlling the activity of microbes, the causes and consequences of structural and functional biodiversity. In addition, the various spatial and temporal heterogeneities of natural soil ecosystems across different scales will be studied. For disentangling the complex interactions of biotic and abiotic processes, the empirical data from synthetic and natural microbial ecosystems and simulation data from virtual microbial ecosystems will be combined and thus the concepts from ecological theory will be adopted. In addition, we will link genes to functions combining multi-omics tools and bioinformatics to scale microbial interaction models towards the diversity relevant for natural ecosystems. Discovery of novel genetic and physiological potentials of microbial communities (microbial resource mining) for contaminant degradation will provide a unique tool to be applied in sustainable biotechnology. Examples of chemicals studied will include mobile polar chemicals (e.g., antibiotics), bulk chemicals (petroleum and derived compounds) or pesticides and mixtures thereof. In addition to degradation of the compounds, we will investigate the formation and fate of transformation products and metabolites, including both immobilized as non-extractable residues. Our results will support future design of sustainable use of chemicals.

Sustainable Aquatic Food Production Systems.

Challenge: Aquaculture delivers heavily on bioeconomy and food security goals, and is expanding at an unparalleled rate of over 6% per year globally. Aquaculture protein production can impact aquatic ecosystems with excess nutrients, excessive demand for limited fodder resources, parasite and disease introduction and genetic pollution. Production must become zero-waste and fully sustainable if aquaculture is to continue to grow. Equally, the enormous diversity of potential new products from aquatic resources such as bioactives and nutrients must be developed towards mass use, e.g., by use in biorefineries.

Approach: We will thus conduct fundamental and applied research to create new knowledge and products from and for the aquaculture of living resources to strengthen the bioeconomy. This requires research along the entire technology readiness spectrum focusing on key steps for sustainability: i) Development of new aquaculture system components and control systems will focus on the reduction of energy and water consumption or reduction or recycling of waste products in order to improve the ecological balance of aquaculture. ii) We will tap into the unused potential of microalgae. In close cooperation with plant science, in particular as relates to metabolites and bioactives as well as the nutrient collection capability of microalgae, we will couple scientific and economic goals to allow algae technology to create a new path that combines active environmental protection with sustainable commodity production for aquaculture use. iii) Optimizing future diets for finfish by testing alternative diet ingredient resources and additives also by integrating plant-based feed options. The search for alternative nutrient sources, especially protein for aquaculture diets, is unrelenting. We will continue to work closely with a wide variety of raw materials providers/producers, as well as specialist product suppliers, to develop and test new products on a wide variety of aquaculture species. Finally, iv) integrated systems to improve the ecological balance of aquaculture units, use resources more effectively and to produce valuable additional products (e.g., usage of residues from aquaculture for biorefineries and industrial biotechnology). Development of production units will be aligned with novel aquaculture species. We will pioneer new saltwater and freshwater IMTA species combinations and aquaponics systems and study them with new feed within ST7.1.

Deliverables (D) and Milestones (M)

- **D7.1 (2026):** Characterize phenotypic and genotypic diversity and function to optimize nutrient use efficiency. **M7.1-1 (2023):** Establish Marginal Field Labs. **M7.1-2 (2024):** Seed bank material phenotypically characterized for improved crop performance. **M7.1-3 (2025):** Optimized cropping system of perennial plants on marginal field established. **M7.1-4 (2026):** Genetic markers for nutrient use efficiency in fluctuating, real-world conditions identified.
- **D7.2 (2026):** Relate functional morphology of organisms to (phenotype and) biomimetic applications. **M7.2-1 (2023):** Establish application of biomimetic principles for multifunctional lightweight products. **M7.2-2 (2024):** Establish systematic use of bionic principles for material substitution. **M7.2-3 (2026):** Develop new CAD-algorithms on principles of morphogenesis.
- **D7.3 (2027):** Provide novel tools for screening and production in industrial cell factories. **M7.3-1 (2025):** Establishment of, e.g., solvent-tolerant *Pseudomonas* strains, acid-tolerant *Ustilago* strains, fast-growing *Vibrio natriegens*, CO_2-fixing photoautotrophic bacteria, acetic acid bacteria for oxidative biotransformation, and microbes with specific capabilities in anaerobic reductive metabolism. **M7.3-2 (2027):** New biosensors for high-throughput screening and single cell-based live-cell imaging from metabolic engineering.
- **D7.4 (2027):** Determine parameters for prediction and valorization of the ecosystem service of contaminant degradation at varying scales. **M7.4-1 (2025):** Experimental approaches for monitoring, understand-

ing and predicting the capacity of ecosystems to degrade chemicals. **M7.4-2 (2027):** Comparative biotransformation analyses conducted in ecosystems.

- **D7.5 (2027):** Proof and disseminate zero-waste aquaculture production system(s) to grow the bioeconomy. **M7.5-1 (2025):** Completed testing of sustainable feeds and production system through full production cycle with commercial partners. **M7.5-2 (2027):** Novel (special) product from zero waste microalgae production registered/patented. **M7.5-3 (2027):** Zero-waste aquaculture model demonstrated for high-value food species in Germany.

Infrastructures and specific resources. The Jülich Plant Phenotyping Center (JPPC) provides the nucleus of German, European and International Plant Phenotyping Networks (DPPN, EPPN, IPPN, EMPHASIS-ESFRI; coordinated by FZJ). The planned Marginal Field Labs (MFL) will be a unique site for testing plants and management practices at low nutrient conditions and complements our field-phenotyping at Campus Kleinaltendorf (with U Bonn). The German Plant Primary Database (PPD) is part of the German National Bioinformatics Infrastructure (de.NBI) and ELIXR-ESFRI. The Jülich Microbial Phenotyping Center (JMPC) combines a unique portfolio of technologies for cultivation of microorganisms, genetic and biochemical analysis, bioinformatics tools and data evaluation systems. The ProVIS Center for Visualizing Biochemical Processes (UFZ) combines infrastructure for visualizing and quantifying biochemical processes and metabolic interactions in biological systems. AWI operates the center for aquaculture research (ZAF) with diverse systems to culture all species in the aquaculture sphere, microalgae, invertebrates and fish. AWI has access to a standardized biomimetic product development process and software and an Additive Manufacturing Lab.

Cooperation partners. U Bielefeld (CEBITEC, Bioinformatics, industrial biotechnology), BioSC partners in plant production, biorefineries, biotechnology and socio-economics, CLIB2021 (industrial biotechnology), Excellence Clusters PhenoRob (AgroRobotics) and CEPLAS (Plant Science). BioEconomy Cluster, ScienceCampus plant-based bioeconomy Halle (WCH), University of Leipzig (microfluidics), DESY, Airbus AG (Lightweight Optimization), Nofima Norway; Uni Auckland, NZ (sustainable Aquaculture).

Risks and Opportunities. Our research has the opportunity to be leading the development of crop breeding tools, novel products and food production systems towards sustainable bioeconomy and in the development and application of genetically encoded biosensors and single-cell analytics in microbial strain development. Our research will give parameters for the (economic) valorization of the ecosystem service of contaminant degradation and establish a comprehensive integrative assessment of the environmental fate and exposure of chemicals. Due to an extensive network, including partners from diverse industries, we have a strong basis for applications. T7 has a high expertise in technology transfer to industry. Risks: strong investments in other continents (e.g., phenotyping) if funding in Germany/Europe stays fragmented. Combination of high structural diversity of chemicals and complexity of environmental systems may not allow for comprehensive predictions of contaminant degradation up to large scale.

Subtopic 7.2 Utilization of renewable carbon and energy sources and engineering of ecosystem functions

Andreas Schmid, UFZ; Wolfgang Wiechert, FZJ

Scope and challenges. The target of ST7.2 is to design, understand, quantify and engineer resource-efficient conversion processes and technologies for bioeconomy products as well as processes supporting ecosystem functions. A broad resource spectrum is considered including biomass-derived material from primary production, residues or waste, inorganic resources such as CO_2 and/or water, as well as resources of fossil origin. At the product side, platform and fine chemicals, microbial and plant secondary metabolites, pharmaceuticals, proteins, materials, energy carriers, and electricity will be addressed. The ST also targets the development of biological and technical systems that are used to mine, degrade, and manage chemicals in natural and technical systems. ST7.2 covers four major technological routes:

- In **biorefineries**, biomass is refined to intermediates or final products. Biomass is efficiently pre-treated and fractionated to make bio-based substrates available for industrial biotechnology and chemistry, or directly converted by microbial consortia.

- **Industrial biotechnology** utilizes bio-based carbon sources, including biorefinery intermediates, to generate value-added products.
- **Photobiotechnology** directly uses H_2O and CO_2 as resources to obtain fine-chemical and high-value products as well as energy carriers like hydrogen.
- **Environmental biotechnology and engineering** generates solutions to reduce the environmental burden of human-made chemicals and enhance resource efficiency.

Main objectives.

- Develop economic and environmentally friendly conversion processes and technologies based on industrial and environmental microbiology, biorefinery technologies, chemical processing and process engineering.
- Exploit the potential of biological resources to enable the synthesis of novel bio-based products by bioinformatics, synthetic biology, metabolic engineering, and chassis strains.
- Develop novel technologies in biocatalytic processing and integrate them in pilot and demonstration infrastructures.
- Design chemicals for sustainable use and defined fate based on scientific understanding of their behavior in environmental systems and develop green technologies for managing water quality and quantity in landscapes and urban spaces.

Work program.

Biorefineries for integrated use of biomass and non-biobased renewable resources.

Challenge: In a circular economy, advanced biorefinery concepts integrate biomass use for food and feed production with value chains for material use while exploiting renewable energies. This covers the production and upgrading of chemical building blocks for material and energetic use (cascaded biomass utilization and poly-generation). Advanced biorefineries will valorized biomass by-products, organic residues or waste streams from agriculture, forestry, aquaculture, food industries, municipal bio-waste etc. to intermediate or final products. They will supply bulk and platform chemicals and energy carriers, while closing nutrient/mineral cycles.

Approach: We will focus on the development of (bio)technologies to efficiently utilize biomass as renewable resource for material and energetic use. In biomass-based processes, the structural and molecular properties of the raw materials require completely new approaches compared to the long-established petrochemical processes. While predominantly non-polar fossil resources and raw materials are classically converted in organic solvents at high temperatures, the highly functionalized components of recent biomass primarily require liquid phase processes at low temperatures in polar solvents containing electrolytes. The fundamental understanding of the properties from the molecular to the macroscopic process scale must be based on a sound scientific fundament. Only this well-founded understanding of the phenomena and mechanisms derived from the material properties of biomass will enable a targeted process development tailored to the starting raw material. The aim of this biorefinery research is the development of flexible, adaptable biorefinery concepts in combination with new strategies for the provision of innovative, biogenic raw materials with an effective return of nutrients to the field. With respect to the fractionation technology, we build on improved fractionation processes (e.g., OrganoCat). Here, the technological readiness of the hitherto developed technology will be elevated to a higher level by establishing downstream and up-stream processing and scaling up to technical scale. We will evaluate the concepts on the basis of economic and societal metrics (cooperation with BioSC and T5). This will build on the direct involvement of the pilot biorefinery NGP^2 (Next Generation Processing and Products – Pilot Biorefinery at RWTH) and the link to RF Energy's biorefinery (thermo-chemical route: BioLIQ, CARF with RF Energy).

Direct biomass valorization avoiding resource and energy-intensive pretreatment and fractionation processes will be developed, relying on the metabolic performance of mainly anaerobic and electroactive microorganisms to produce bulk chemicals and energy carriers, e.g., carboxylic acids, higher alcohols, methane, and higher alkanes. The ecological, physiological and thermodynamic constraints of reactor microbiomes as well as their metabolic pathways and trophic interactions will be deciphered by applied microbial ecology (including 'omics' techniques and systems biology) targeting different levels of complexity from communities over enriched and constructed consortia to pure cultures. Beyond solid and liquid organic feedstock, gases (H_2/CO_2 or syngas, e.g., from gasification of dry biomass) will be utilized as carbon and energy sources in autotrophic and mixotrophic processes. In this context, electricity transfer methods provide flexible tools for process engineering.

The combined use of bio-based and non-biobased renewable resources will be targeted by electrobiotechnology and Power-to-X approaches, thereby coupling the chemical and energy sectors. The concept of electro-biorefineries provides an umbrella for the foreseen activities. We will especially focus on i) providing biogenic chemical feedstock for subsequent microbial conversions (e.g., bioelectrochemical CO_2-reduction), and ii) upgrading of reactor microbiome-derived products using electroorganic syntheses. Microbial electrosyntheses based on the direct wiring of microbial metabolism and electrode reactions will be investigated exploiting reactor microbiomes harboring electroactive microorganisms as well as electroactive pure cultures.

Research activities will integrate fundamental aspects, process characterization as well as process and reactor engineering. Storage and upgrading options for gaseous energy carriers will be developed and assessed with regard to ecological risks, sustainability, and technical feasibility.

Utilization of bio-based carbon sources for value-added products.

Challenge: To valorize the huge potential of biological resources (ST7.1), microbial production strains, enzymes, and chemical transformation steps need to be developed, integrated, and adapted to technical environments, thus enabling the conversion of renewable carbon sources (e.g., C6 and C5 sugars, C1 compounds, crude glycerol) and of waste-streams such as plastics into value-added products (chemicals, pharmaceuticals, proteins). In addition to the development of innovative new products and greener alternatives to existing production routes, the resulting processes must be optimized (among other criteria) for space-time yield, selectivity, economic and ecological efficiency.

Approach: The first pillar for an efficient microbial conversion of renewable carbon sources is the creation of efficient producer strains. We will advance rational strain design using advanced synthetic biology tools (e.g., CRISPR-Cas-based genome editing, systems metabolic and transport engineering, genome-reduced chassis strains). The overall aim is to create strains with a metabolic highway from the substrates to the desired products. The advances in DNA synthesis open up novel possibilities in the fabrication of genetic constructs for known or novel metabolic pathways combining genes from single or multiple donor organisms including suitable control elements. Microbial production of natural products with potential applications in chemical or pharmaceutical industries offers great opportunities for valorizing biological diversity. Biosynthetic pathways for a variety of secondary metabolites will be transplanted into microbial chassis strains to enable production of, for example, plant polyphenols with nutritional or pharmaceutical applications. Strains that contain rationally designed pathways for multistep biocatalysis to produce, for example, polymer building blocks, will be engineered. In parallel, the metabolism of the production hosts will be optimized to ensure sufficient precursor and energy supply for the envisaged pathway. As a promising new approach, the design and suitability of synthetic microbial communities for catalyzing complex conversion processes will be evaluated. This will include the combination of photoautotrophic and chemoheterotrophic microorganisms to exploit complementary properties such as mutual supply with O_2 and CO_2 and biofilm formation capabilities.

Rational approaches for strain development will be complemented by evolutionary approaches. Major targets will be the application of high-throughput screening of strain and enzyme libraries using genetically encoded biosensors combined with FACS (ST7.1) and ALE (Adaptive Laboratory Evolution). ALE has a very high potential for strain optimization, for example, by coupling growth to product formation, particularly when combined with robotics and 'smart' strains specifically engineered for this approach. Genome sequence analysis of the evolved organisms will yield unknown targets and valuable new insights for strain optimization by metabolic engineering. Besides metabolites, another target addressed by high-throughput methods is the secretory production of proteins with pharmaceutical or industrial applications. The huge parameter spaces (including expression strength, signal peptide libraries, media composition, process parameters) will be screened.

Bioprocess development is the second pillar of industrial biotechnology. It embraces the quantitative characterization of microbial producer strains in technical environments and the optimization of technical performance criteria in close cooperation with the research focused on microbial strain development. At present, process development cannot keep pace with the generation of new producer strains. Miniaturization, automation, and digitalization are the pacemakers for speeding up process development and revolutionize industry. Cutting-edge examples will demonstrate the potential of automated process development. Miniaturized parallel experimentation in combination with the application of 'omics' tools (ST7.1) leads to a dramatic information overflow, necessitating tailored data science approaches accompanied by mechanistic modeling to achieve a deeper understanding and design appropriate experiments. Continuous processing and scale-up still constitute highly critical aspects in industrial process development. Facilitation of continuous processing is targeted by a novel biofilm reactor platform. Here, the response of producer strains to fluctuating technical environments must be understood. For this purpose, novel scale-down simulators, microfluidic single-cell devices and analysis tools (ST7.1), as well as spatio-temporally resolved process simulation will be employed.

Conversion processes based on microbial producer strains will be complemented by multi-step enzymatic synthesis. For the enantioselective synthesis of high-value active pharmaceutical ingredients with several stereogenic elements, synthetic enzyme cascades based on the modular combination of enzymes from toolboxes will be established and highly controllable processes will lead to maximal space-time yields, selectivity, and eco-efficiency. In this context, also the stimuli-responsive regulation of enzyme activity will be studied. Integrated engineering covering the enzymes, the solvents, and reaction parameters and reactor design is crucial for success. One of the most critical preconditions for the industrial usage of enzymes is their cheap availability and robustness with respect to technical environments. For this purpose, enzymes will be optimized for long-term stability and novel immobilization techniques for enzyme reuse will be developed.

As an innovative extension to classical biotechnological conversion processes exclusively using biological catalysts, hybrid bio/chemo-catalytic processes will be developed based on combinations of whole-cell biocatalysts, enzymes, and chemo-catalysts integrated with novel (bio)reactor technology, including e.g., flow chemistry systems and bioelectrochemical reactor systems. Such hybrid processes offer new opportunities for manufacturing and foster the linkage of biological and chemical catalysis. Computational design and integrated process engineering will be crucial to stabilize and optimize multi-stage processes of this complexity.

Direct use of H_2O, CO_2, and sunlight for chemicals and energy carriers.

Challenge: The direct use of inorganic renewable resources such as CO_2 and water and thereby the decoupling of the energetically rather inefficient biomass formation (1% to maximally 4.5% of sunlight energy converted to chemical energy), constitutes a major challenge. Besides Power-to-X strategies, this can be realized by the utilization of photoautotrophic microbes such as cyanobacteria. To date, the use of photoautotrophic microbes is restricted to low volume – high price products due to persisting challenges in realizing high cell density cultivation as a prerequisite for high productivities, stable catalytic performance, continuous operation, and scalability at reasonable costs.

Approach: New process concepts and strain design strategies will boost photobiotechnology. Rational strain engineering based on systems biotechnology taking carbon as well as electron flow will be combined with novel cultivation and reactor concepts to solve the issues of low cell densities and insufficient reaction stabilities. To develop cyanobacteria into photobiocatalysts synthesizing chemicals and fuels from water and CO_2, it is essential to understand the complex metabolic and regulatory networks for energy generation and carbon flux.

Metabolic processes explicitly including the photosynthetic light reactions will be monitored using 'omics' tools. The regulation and impact of storage compound synthesis as potential unthrifty carbon and electron sink will be investigated to maximize energy yields for product formation. As key methods, CRISPR/Cas9-based strategies will be developed to knock out/down/in genes. Manipulation targets will be identified using genome-scale metabolic and regulatory models.

The development of cyanobacteria-based cell factories for redox biocatalysis will be a main target. This involves the direct coupling of oxidoreductases to the photosynthetic electron transport chain, to directly tap the electrons derived from photosynthetic water oxidation for the production of industrial chemicals and energy carriers with hydrogen as a main target. In addition, product formation relying on photosynthetic CO_2 fixation will be targeted. This also will include two-stage processes where a cellular metabolite such as glycolate is produced by photoautotrophic organisms, which then serves as carbon source for established industrial production strains like *E. coli* or pseudomonads for synthesis of value-added compounds. Photosynthetic energy yields in the range of 10% for products relying on CO_2 fixation and up to 50% for products only relying on light reactions, such as H_2, can be envisaged.

Last but not least, we will develop suitable cultivation solutions enabling the operation of phototrophs at high cell densities (link to ST7.1 for algae). As a main approach, surface-attached biofilms will be applied, constituted of either single species or defined synthetic consortia. Biofilms are very robust, enable high cell densities and continuously regenerate themselves. Light assimilation and penetration are key issues when working with photoautotrophic organisms growing in multi-layers. Photosynthetic efficiency and photoinhibitory effects in light-exposed biofilm layers will be analyzed on a single cell level as well as for entire biofilms using ProVIS facilities. Assisted by a multiscale biofilm model, cultivation of photoautotrophic biofilms will be established in novel tubular microreactors with a maximized surface area to volume ratio.

Environmental biotechnology and engineering for a sustainable use of chemicals.

Challenge: The increasing level of urbanization generates ecosystem pressure particularly at urban-rural interfaces. Options for recycling, local storage and re-use of water in urban and peri-urban environments need to be investigated and developed (ST7.1). Especially waterborne polar chemicals (e.g., antimicrobials, pesticides and hormones) are challenging due to their often low concentrations, high mobility and structural diversity. Tailor-made implementation of environmental biotechnology and decentralized engineering solutions into urban and peri-urban water management is needed to limit anthropogenic stress on aquatic (and terrestrial) ecosystems and human water resources (T5). Furthermore, changes in climate may cause flooding effects or droughts – both a challenge for urban water and wastewater infrastructures.

Approach: Environmental (bio-) technological tools to produce resilient water treatment technologies will be designed for the removal of chemicals and complex mixtures thereof will be developed. Multi-functional and decentralized process solutions for water quality control will rely on a constantly updated 'toolbox' for chemicals' removal, including improved, nature-based technologies and new materials. This includes the development of specialized separation materials and the design of engineering approaches for decentralized water and wastewater treatment for removal of polar, highly water-soluble substances. Combined with insights about context-specific factors and trends inc

luding demographic and climate parameters, patterns of water usage, public risk awareness and infrastructural needs (T5) will form the basis for models of resilient green system architecture for the 'city of the future' and the co-design and implementation of robust nature-based technologies (link to ST7.1). In parallel, work on advanced material design and method improvement for in situ and ex situ technologies is essential.

Relying on cutting-edge methods from analytical chemistry and ecotoxicology, inexpensive and user-friendly screening tools for quantifying mixtures and their ecotoxicological effects in treated water will then be developed and tested (T9). These results have the potential to create a paradigm shift in the engineering design process. Resilient water treatment technologies specifically designed for the removal of chemicals in real water matrices (T5) will be developed.

Deliverables (D) and Milestones (M)

- **D7.6 (2027)**: Development and improvement of biotechnological processes of mainly anaerobic and electroactive microorganisms to produce bulk chemicals and energy carriers. **M7.6-1 (2024):** Analysis of ecological, physiological and thermodynamic constraints of reactor microbiomes as well as their metabolic pathways and trophic interactions at levels of communities, enriched and constructed consortia to pure cultures.
- **D7.7 (2024)**: Establishment of biosynthetic pathways for a variety of secondary metabolites into microbial chassis strains. **M7.7-1 (2024):** Production of plant polyphenols with nutritional or pharmaceutical applications.
- **D7.8 (2027)**: Development of cyanobacteria-based cell factories and process concepts for redox biocatalysis coupled to photosynthetic water oxidation and electron transport for the production of industrial chemicals and energy carriers with hydrogen. **M7.8-1 (2024)**: Cell factories for photosynthesis-driven redox catalysis with optimized electron transfer. **M7.8-2 (2025):** High-density cultivation of photoautotrophic biofilms in tubular microreactors.

- **D7.9 (2027)**: Treatment technologies specifically designed for the removal of mobile and highly polar chemicals and complex mixtures thereof from urban water streams. **M7.9-1 (2025)**: Materials for in situ and ex situ technologies for chemical removal. **M7.9-2 (2027)**: Geographic information system (GIS) based models of resilient green-system solutions for urban water management established.

Infrastructures and specific resources. Jülich Plant Phenotyping Center, Jülich Microbial Phenotyping Center, MiBioLab, decentralized wastewater treatment research infrastructure, Langenreichenbach site with focus on the design and optimization of ecotechnologies. BDZ Demonstration Site in Leipzig with focus on the comparison of decentralized wastewater treatment technologies. Pilot facility, Fuheis, Jordan, focus on adapting selected technologies to arid climate conditions. KIT: Membrane technology for water technologies.

Cooperation partners. AVT (RWTH Aachen), Excellence Cluster Fuel Science Center, DBFZ and BioEconomy Cluster on novel biorefinery concepts, CLIB2021 and MiKaT as well as industry interaction with BASF, Evonik Industries, Bayer on novel biotechnology routes and applications; Real Urban Lab 'German Model City Leipzig', CAS Beijing, Technion & Ben Gurion University and IIT Chennai India on environmental engineering solutions.

Risks and Opportunities. Efficient microbial synthesis of natural products provides access to numerous compounds with pharmaceutical or health-promoting properties, many of which are not accessible in other ways; effective H_2 production driven by sunlight; effective transfer possibilities of research outcome to City of Leipzig as a German Model City; treatment technologies specifically designed for the removal of highly polar chemicals may form alternative for a fourth wastewater treatment step; renewable energies coupled to water treatment technologies as step-change in process efficiency and accessibility. Risks: Unstable ownership/ investor relationship at Real Urban Lab 'German Model City Leipzig'; microbial or enzymatic synthesis of value-added products is a highly competitive research area; early development stage of photobiotechnology; up-scalability of novel (nano)materials.

Subtopic 7.3 Agro-biogeosystems: controls, feedbacks and impact

Jan Vanderborght, FZJ

Scope and challenges. ST7.3 will focus on agro-biogeosystems and the interplay between producing ecosystems (focusing on agricultural and forest ecosystems) and the environment. Impact and feedback of primary production on the environmental compartments (soil, atmosphere, water) will be analyzed to develop and optimize integrated systemic approaches that minimize feedback loops with negative impacts. GHG emissions from the agricultural sector in the EU-28 accounted for 471 million tons of CO_2 equivalents in 2012 (10% of total GHG emissions (EC)). Thus, results from ST7.3 serve as a basis for climate-smart and climate-resilient agri/silviculture. The focus is on fundamental understanding of soil-plant-atmosphere processes and nutrient cycling (ST7.1) in agroecosystems across scales, aiming at a better comprehension of the interplay between hydrologic, biotic, and geochemical processes. This knowledge forms the basis of integrated multi-scale terrestrial modeling that represents producing ecosystems, allows to design near real-time management, generates knowledge/information from large data streams (from simulation and measurement), and contributes to a digital bioeconomy. Quantitative analysis of production systems on ecosystem services will be done with respect to atmosphere, water, biogeochemical cycles and local climate (T1 and T5).

Main objectives.

- Quantify environmental impact, control and feedback as the basis for design of sustainable management of production systems.
- Develop innovative and sustainable management strategies based on fundamental understanding of hydrological and biogeochemical processes in the soil-plant-atmosphere system across scales.
- Identify and target ecosystem functions/services to reduce anthropogenic impact and to support the quantification and management of ecosystem services.
- Develop integrated, multi-scale observation and simulation platforms utilizing exascale computing of terrestrial systems, near real-time forecasting of states and fluxes in producing systems to evaluate land use/ management and climate change scenarios.

Work program.

Novel monitoring technologies for sustainable management of agro-biogeosystems.

Challenge: To improve understanding of hydrological and biogeochemical processes across scales and to support sustainable management of agro-biogeosystems, there is a need for observation technologies and strategies to integrate observational information into models to improve the sustainability and the production use of agro-biogeosystems.

Approach: A unique experimental facility for experiments in large mesocosms (AGRASIM) will be developed, and will observe the soil-plant-atmosphere continuum. In order to further improve our ability to observe the soil compartment at this mesocosm scale, a high-resolution imaging system based on electromagnetic wave propagation will be developed. The added value of this system will be highlighted using manipulation experiments targeting the improved understanding of drought conditions on production systems. Knowledge on the within-field variability of soil properties still is a limiting factor for the quantification of environmental impacts and controls within sustainable production systems. Novel geophysical technologies and interpretation strategies will be developed that address this lack of information and enable improved within-field management of production systems. Together with observations from drones and remote sensing platforms, geophysical observation technologies will be integrated into a multi-scale observation platform that supports the near real-time management of production systems (Fig. 7.4). Special focus will be on the quantification of solar-induced chlorophyll fluorescence (SIF) from plants (with ST7.1), which can be measured across scales from ground-based platforms and the high-performance airborne imaging sensor 'HyPlant'. SIF in combination with knowledge about soil properties serves as a novel indicator for early vegetation stress detection and will be used to improve our carbon and water models. SIF measurements will be available from the future global FLEX satellite mission of the European Space Agency (ESA). We will support data product development and contribute to the validation of the satellite products. In order to maximize the value of the observations, an integration of the observational data on the laboratory, field, or regional scale in the available simulation platforms is essential. This requires the development of operators to link measured and modeled state variables and concepts how observed patterns in properties can be transformed into relevant soil and crop information.

Biogeochemical and hydrological controls on agro-biogeosystems.

Challenge: Sustainable biomass production is characterized by low use of resources, high nutrient and water use efficiency, and preservation of soil health as well as air and water quality. Achieving and maintaining sustainability of agro-biogeosystems and their feedbacks in a changing world requires deep knowledge of the underlying biogeochemical and hydrological processes and their response to global change.

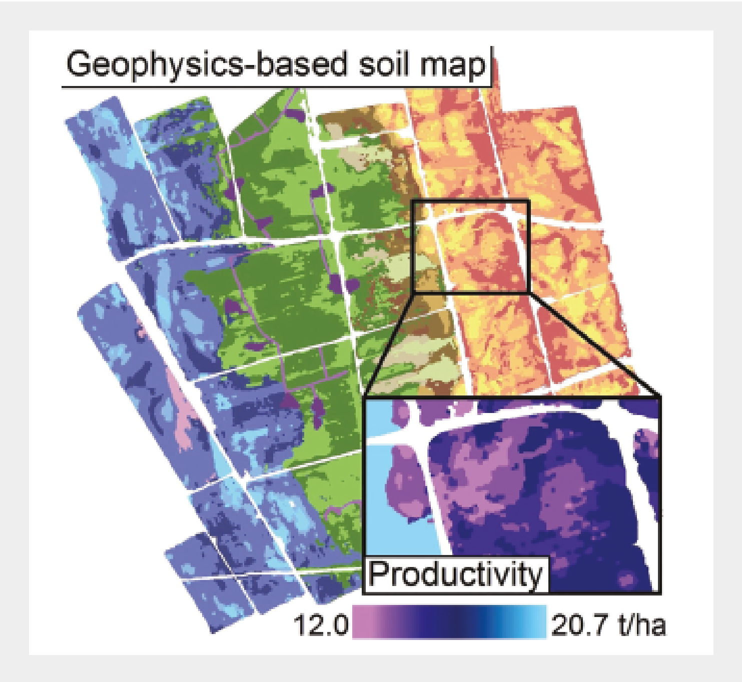


Fig. 7.4: Digital soil map of the experimental site at Selhausen derived from EMI surveys and predicted sugar beet productivity.

Approach: We will perform targeted experiments in the AGRASIM facility deduced from research described above and focused on a range of extreme conditions to identify and quantify the effect of multiple stressors on agricultural food production and the associated nutrient and water use efficiency. This work will be complemented by extensive long-term monitoring of trends in biogeochemical and hydrological states and fluxes in managed terrestrial ecosystems (cropland, grassland, forest) to assess their resilience to climate change and to quantify land surface-atmosphere-hydrosphere feedbacks in response to changing environmental conditions using stable isotopes and TERENO, ICOS and eLTER infrastructures. Furthermore, short-term intensive field campaigns will be conducted within MOSES for the detailed analysis of system responses to extreme events (e.g., droughts and floods) to identify potential tipping points and to achieve a better understanding of system recovery. The combined approach utilizing large-scale infrastructure will be complemented by process studies towards understanding the role of observation scale on the assessment and prediction of GHG and evapotranspiration fluxes as well as elemental cycling and nanoparticle fluxes in managed terrestrial ecosystems. Studies on soil-root interactions will improve the understanding of the interplay between surface and subsurface processes, which in turn will allow for an improved quantitative description of plant performance and cross-compartmental water, energy and matter fluxes (ST7.1). Our research will provide the data basis and process understanding to enable realistic simulations of environmental controls, feedbacks and impacts on agro-biogeosystems for a range of future climatic and environmental conditions (see below). This in turn is the prerequisite for the development of innovative, sustainable management strategies fit for the future.

Prediction of environmental controls, feedbacks and impact.

Challenge: To select options for a climate-smart and sustainable agriculture based on circular resource cycles, accurate predictions of the impact of management on the functioning of terrestrial systems are required. To support a digitalized agriculture, near real-time forecasts of the systems' short-term evolution must be provided. Reliable predictions and forecasts require the consideration of feedback loops in the system and they should also be consistent with all information about the current and past states of the system.

Approach: Mechanistic process models of the terrestrial system will be developed that integrate multi-source information obtained from multiscale sensing platforms across space-time scales with the detailed process knowledge obtained from experimental facilities. These models will predict in a fully consistent manner states and fluxes of the terrestrial system including feedback loops emerging from the process simulations. A coupled soil process-functional structural plant simulation platform will be developed as counterpart of the AGRASIM experimental platform. This simulation platform will identify optimal plant, soil, and management combinations under future climatic conditions, consider within-field soil variability and evaluate the impact of agricultural management strategies leading to circular resource cycles on the long-term evolution of soil functions. Predictions of the impact of land use/management in a future climate on different compartments of the terrestrial system at regional up to continental scales will be provided using the fully coupled terrestrial system model TerrSysMP (CTA ESM). By linking the multivariate, multiscale and cross-compartmental data-assimilation platform TerrSysMP-PDAF with the DE data platform, a link between simulations and measurement data from different observation platforms will be established and used to make real-time forecasts of states and fluxes in the terrestrial system and to generate a fully consistent dataset of current and past ecosystem states (ecosystem reanalysis for eLTER). Accurate representation of interactions and feedbacks requires high-resolution simulations and exascale computing, which will be made possible by co-designing dedicated hardware and software for Earth system simulators in JL-ExaESM.

Deliverables (D) and Milestones (M)

- **D7.9 (2027):** Non-invasive monitoring and imaging technologies to understand production systems and support their sustainable management. **M7.9-1 (2024):** Geophysical imaging methods for experimental platforms and within-field management. **M7.9-2 (2027):** Multiscale observation platforms including satellite-based SIF measurements for crop management.
- **D7.10 (2027):** Experimental platforms and experiments providing understanding of biogeochemical and hydrological fluxes in agro-biogeosystems. **M7.10-1 (2024):** AGRASIM mesocosm experiments to evaluate the impact of multiple stressors on production systems. **M7.10-2 (2027):** Long-term monitoring of terrestrial systems combined with intensive field campaigns to observe and understand trends and responses to extreme events.

- **D7.11 (2027):** Predictions of and seamless forecasts for optimal management and its impacts on resource cycles in terrestrial systems. **M7.11-1 (2024):** Soil process-functional structural plant simulation platform. **M7.11-2 (2027):** Seamless forecasts of the state of production systems at continental scale with TerrSysMP. **M7.11-3 (2027):** Ecosystem reanalysis providing a benchmark against which future changes and extremes can be evaluated.

Infrastructures and specific resources. We operate and contribute to several research infrastructures (AGRASIM, TERENO, MOSES) and the modeling competence center TerrSys. AGRASIM is an indoor mesocosm research facility to analyze and optimize agricultural systems under present and future climatic conditions. It will provide a crucial link between lab and lysimeter-based studies and field and catchment-based platforms (tube-rhizotron facility Selhausen, TERENO) enabling seamless hydrological and biogeochemical research across scales. TERENO is a research platform for long-term observation and modeling of environmental processes in the framework of global change. It is coordinated by FZJ and embedded in national and international platforms (ICOS-D, ICOS, eLTER). The modular observation platform MOSES is used to improve our understanding of event-based processes caused by heatwaves and hydrologic extremes. Both TERENO and MOSES provide the basis for the further development and validation of the TerrSysMP simulation platform.

Cooperation partners. Geoverbund ABC/J, Bioeconomy Science Center (BioSC). Excellence Cluster PhenoRob (U Bonn) novel and automated agricultural management systems. International strategic partners are from ESFRI projects eLTER and ICOS, CZEN (monitoring ecosystems) as well as from the international soil modeling consortium ISMC, the World Climate Research Program GEWEX and CORDEX projects (simulation and modeling).

Risks and Opportunities. Geoverbund and HPSC are ideal platforms to develop strategic research in Africa; Risk: lack of funding to continue research infrastructures like TERENO.

E) Previous achievements of the contributing centers and infrastructures

Expertise and preliminary work. Most of the researchers of T7 have not been in Programs of the RF E&E in PoF III, but did their research in the RF Key Technologies and RF Energy in PoF III. The opportunity to bundle bioeconomy research in the Helmholtz Association within this Program was therefore highly appreciated and builds on diverse previous achievements.

FZJ bioeconomy research builds strong regional networks and science cooperation like BioSC, Geoverbund or CLIiB2021. Bioeconomy researchers are members of three DFG excellence clusters, namely PhenoRob (agro-robotics), CEPLAS2 (plant sciences) and Fuels Science Center (conversion of renewable carbon). Microbial biotechnology at FZJ has a long record of accomplishment of developing and applying microorganisms and isolated enzymes for the synthesis of value-added products from renewable carbon sources. The focus is on metabolic and regulatory networks of industrial microbes and strain development, cell-based and cell-free bioprocesses, identification, isolation and characterization of enzymes and their application in biotechnology, and on chemoenzymatic processes for the synthesis of chiral, enantiomerically pure intermediates for natural products. Plant Sciences at FZJ is leading in plant phenotyping integrating the search for novel traits and the development of state-of-the-art technology for screening. Based on its unique technological capability and expertise in crop physiology the institute has developed the German, European and global plant phenotyping landscape in recent years and set up major international activities in crop phenotyping like DPPN, EMPHASIS or IPPN. FZJ is also leading in developing alternative biomass crops for integrated biorefinery approaches for bulk and high-value secondary substances (circular economy). Agrosphere research at FZJ combines the development and use of observation technologies with unique cross-scale experimental studies and advanced integrated terrestrial models to provide solutions for a sustainable use of agro-biogeosystems. It plays a leading role in international activities such as ISMC, ICOS and eLTER with a focus on hydrological and biogeochemical process studies and the development of forecasting tools for climate-smart agriculture. FZJ hosts the coordination office of ISMC for the advancement of soil modeling.

UFZ integrates matter fluxes with organismic ecology in complex microbial ecosystems and plays a leading role in detecting microbial hotspots and identifying key factors controlling the long-term functional ecological performance with regard to biodegradation. New technologies for in-and ex situ remediation are developed. This nature-based solution approach is also followed for the ecoefficient production of chemicals and energy carriers focusing on the control and diversification of anaerobic digestion processes, electrobiotechnology and its combination with biorefinery processing, and photobiotechnology for CO_2 use and redox biocatalysis.

KIT has set-up state-of-the-art infrastructure for materials and process development with characterization tools for materials through to water pollutants and micropollutants.

AWI has been establishing strong ties between research and industry through the Institute for Marine Resources (IMARE), and is active in all Technology Readiness Levels (TRL).

Uniqueness. Partners in T7 are in a unique position to integrate bioeconomy research and technical solutions to utilize biological and environmental resources in a sustainable way by integrating into this Program. All four participating centers have unique **technological platforms,** which they combine with biological, chemical and environmental process expertise towards integrated approaches targeting for sustainable bioeconomy. Multi-scale and multi-temporal analyses are key to understand and optimize production system from multi-omics analytics for the plant and microbial biotechnology and aquaculture organisms, advanced phenotyping technologies for crops (EPPN, EMPHASIS) and microbes (JMPC), state-of-the-art observation and experimental infrastructures for chemicals in the environment and agroecosystems (e.g., TERENO, AGRASIM) as well as demonstrators for production in crops (various field stations), microbes and aquaculture (e.g., ZAF) and biorefineries (e.g., electro-biorefineries, NGP[2]). These platforms are combined with deep knowledge of structure-function relationships as well as engineering competence and modern approaches for modeling (e.g., TerrSYSMP) and integration at relevant spatial and temporal scales.

F) Collaboration and transfer

Partners. Within T7 a Topic Board will be established that represents all Subtopics and participating centers. The Topic Board will discuss in an agile management approach scientific advancements, opportunities to interact between Subtopics as well as links and future directions to other Topics and with research outside of the program in bioeconomy-related research. Research of T7 is tightly embedded into the German, European and international community on sustainable bioeconomy. These established links are important to extend our research beyond the Earth system focus of the Program. T7 plays a crucial role for the Program in opening links to parts of the German and international research community that are essential for the systemic approach, but hitherto not in the core focus of Earth System Research.

Positioning of the Topic in international research. Research in T7 has strong science links as well as implementation needs internationally. Researchers are directly involved in European Research Infrastructures (ESFRI) by coordinating EMPHASIS and active participation in building eLTER (FZJ, UFZ). However, the international perspective of our research develops from the need to establish bioeconomy in hotspots of economic development. Consequently, we focus our international efforts on SE-Asia (e.g., Thailand, China, India), Latin America and Africa. The later will become a focus in integrated action between ST7.1, 7.2 and 7.3, where existing networks will be opened to all colleagues by specific measures organized by the Topic: e.g., workshops with WASCAL/SASSCAL in the wider context of bioeconomy.

Cross-Cutting Activities and Alliances. T7 is involved in integrated measures with respect to data/information sciences (Helmholtz Analytics framework, Helmholtz Data Federation, structural biology). Agro-biogeosystem research (ST7.3) is integrated in the ongoing CTAs MOSES, TERENO, ESM and Digital Earth as well as in as the CARFs REKLIM and HI-CAM. Increased involvement of ST7.1 and ST7.2 in these initiatives will be established during PoF IV. Bioinformatics in Bioeconomy will be linked with the NFDI initiative for research data infrastructures, and with the Helmholtz Incubator, as well as the RF E&E cross-cutting data initiative.

Name of strategic partner	Fields of cooperation	Joint efforts + perspectives
EMPHASIS ESFRI project https://emphasis.plant-phenotyping.eu/	**Research, Knowledge transfer, Talent Management (since 2018)** • Development of infrastructures and providing access for multi-scale phenotyping to analyze genotype performance in diverse environments and quantify the diversity of traits	• Develop an integrated Pan-European infrastructure of instrumented facilities for plant breeding • Design and establishment of the European phenotyping data systems • Develop, evaluate and disseminate novel phenotyping technologies
eLTER **ESFRI project** https://www.lter-europe.net/	**Research, Knowledge transfer, Talent Management (since 2018)** • Development of a European research infrastructure on Integrated European Long-Term Ecosystem, Critical Zone & Socio-Ecological Research Infrastructure	• Systematic coverage of major European terrestrial, freshwater and transitional water environments • Integrated observations across the critical zone • Interactions between abiotic and biotic ecosystem components
Bioeconomy Science Center (BioSC) with U Bonn, U Düsseldorf, RWTH Aachen www.biosc.de	**Research, Knowledge transfer, Talent Management (since 2010)** • Smart management for plant performance • Integrated biorefineries for sustainable production and processing • Transformations for high-value chemicals	• Development of integrated bioeconomy concepts • Integration of bioeconomy in a circular, hybrid economy • Model region Bioeconomy Rhineland • Socio-economy of bioeconomy and economic transformation
Cluster of Excellence PhenoRob with U Bonn and FhG www.phenorob.de	**Research, Knowledge transfer, Talent Management, Infrastructure (since 2019)** • Machine learning and robotics • Phenotyping • Modeling • Socio-economy of technology transfer	• Development agrorobotics for phenotyping and crop management • Model-based crop management and breeding
Cluster of Excellence CEPLAS2 with U Düsseldorf, U Cologne, MPI Cologne www.ceplas.eu	**Research, Knowledge transfer, Talent Management (since 2013)** • Development and metabolism • Plant Microbiota Metabolic Networks • Synthetic and Reconstruction Biology • Theoretical Plant Biology and Data Science	• Crop efficiency and stress resilience • Plant-microbe interactions • Bioinformatics • Pre-breeding
MiKaT – Center for Biocatalysis U Leipzig, Halle, Dresden, Freiberg, FhG CBP, IPB Halle www.mikat.info	**Research, Knowledge transfer, Talent Management (since 2015)** • Development of an expert network for biocatalysis • Basis for national and international research projects	• Excellent and joint R&D and transfer in industrial biotechnology/bioeconomy • Coordination of teaching and R&D • Support of the educational goals of the BioEconomy Cluster

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Cross-Cutting Activities and Alliances. T7 is involved in integrated measures with respect to data/information sciences (Helmholtz Analytics framework, Helmholtz Data Federation, structural biology). Agro-bio-geosystem research (ST7.3) is integrated in the ongoing CTAs MOSES, TERENO, ESM and Digital Earth as well as in as the CARFs REKLIM and HI-CAM. Increased involvement of ST7.1 and ST7.2 in these initiatives will be established during PoF IV. Bioinformatics in Bioeconomy will be linked with the NFDI initiative for research data infrastructures, and with the Helmholtz Incubator, as well as the RF E&E cross-cutting data initiative.

Bioeconomy is tightly linked to other elements of the Earth system and their performance. Agricultural and aquaculture production occurs in close interaction with terrestrial landscapes in rural as well as in urban settings. This is also where microbial engineered systems and biomimetic structures become effective (T1, T5 and CARF Resilient Urban Spaces). Coastal areas (T4) integrate – e.g., in river deltas – zones for many bioeconomy-related activities. Extreme events (CTA Extremes) play an important role to establish resilient production systems, and T7 has strong experience and demand in remote sensing (CARF Remote Sensing). Human health is determined by the availability of nutritious, diverse and healthy food as well as food/feed additives. Production systems are an important source for chemicals in the environment and on human health (T9, CARF MACE). The energy sector and bioeconomy research (CARF Bioeconomy meets Energy) interact strongly in biorefineries and in the integration of energy carriers and electrical power as well as in energy systems design and bioeconomy implementation linked to distributed energy and renewable carbon sources.

Transfer and contribution to SynCom. T7 has exceptionally strong experience in implementation of knowledge, technologies, processes and products in agriculture, industry and society. We have a long-standing track record in licensing, generating spin-offs and integration of research results in regulation. Collaborative and strategic research with companies is a particular strength. We have established dedicated technology transfer centers: AWI has established a center focusing on biomimetic design for lightweight structures and has expertise in start-ups in this area. FZJ will establish Innovation Centers for Digital Bioeconomy and for Integrated Biorefineries (BioökonomieRevier). UFZ is partner in the BioEconomy Cluster Central Germany and is pursuing the establishment of the Real Urban Lab 'German Model City Leipzig'. KIT has intensive technology transfer that will also allow international dissemination of the developed technological solutions

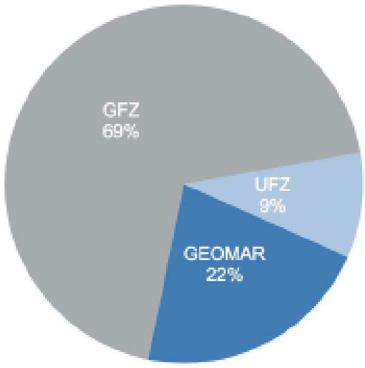
Interaction with SynCom is highly important due to the unique competence of T7 on the use of natural resources and human impact by bioeconomy activities. SynCom will provide an important interface with Earth System Research to proactively discuss the balance between impact and use of resources. Regional implementation and positive attitude of the public and in politics for sustainable bioeconomy for food security and non-food applications is a strong basis for communication and an important task for implementation of our results.

Executive Summary

- T7 is uniquely positioned to balance the demand for products based on natural resources and their stewardship by integrating bioeconomy research into Earth System Research. Our research focuses on improving biological and environmental resources for sustainable production, utilization of renewable carbon and bio-inspired technological systems. Results will support circular economy concepts and Earth system management.
- Research capabilities of T7 uniquely interlink biological, chemical, engineering and digital sciences. This exceptional profile allows unique quantitative approaches to optimize crops and agricultural production, aquaculture, microbial and biotechnology systems for efficient use, novel products and stewardship of natural resources.
- By delivering solutions for a sustainable bioeconomy, T7 contributes directly and in cooperation with other Topics to providing a sustainable food/feed source for a growing population (Objective 7) as well as integrating bioeconomy into a circular economy approach for non-food product and energy (8). Bioeconomy-related production drives and is affected by climate change (2, 3, 10) and extreme environmental events (1) in terrestrial and marine ecosystems (6). Generating innovative solutions in bioeconomy is central to improving environmental and human health (9).

Topic 8: Georesources for the Energy Transition and a High-Tech Society

Spokesperson: Sarah A. Gleeson, GFZ; Deputy: Mark Hannington, GEOMAR



The mission of Topic 8 is to provide a scientific basis for accessing safe, clean energy and the raw materials needed for our 21st-century infrastructure, enabling the energy transition and supporting a growing circular economy. To this end, Topic 8 will address two key challenges related to georesources for the energy transition and a high-tech society: where to find the resources that we need today and in the future, and how to access those resources in the most sustainable way.

A) Scope and challenge of the Topic

Research subject. The secure, sustainable, and safe supply of energy and mineral resources for a growing global population is a major challenge for the future. The easily accessible resources close to the Earth's surface have already been found; the resources of the future will have to be sourced from greater depths, and/or be processed with greater efficiency. This requires new quantitative understanding, and better models, of the structure, composition and potential of the Earth's upper crust. Topic 8 (T8) is aimed at revealing the architecture, composition, and the physical and chemical dynamics of crustal systems that will guide us to metals and geothermal resources, and which will also inform solutions for their utilization. Within the next decade we will transition from near-surface exploitation to depth, requiring new approaches for safe underground utilization of energy and mineral resources and realizing the storage potential of the subsurface. This 'deep revolution' is driven not only by the need for new resources but also by increasing demands to limit the use of the near-surface environment. The over-arching goal is to diversify our resource portfolio for a safer, cleaner, and more dependable future, which means developing deeper geothermal energy as a reliable domestic energy source, deeper raw-materials resources to replace exhausted, near-surface, deposits (including in the deep oceans), and reliable underground storage of both energy and energy waste.

Explanation and justification of research. Global energy and raw material use is expanding rapidly. More than 70% of new energy demand is still met by oil, natural gas and coal, resulting in continuing increases in CO_2 emissions.[212] Despite the 'Energy Transition', Germany imports 61% of its energy[213] and also remains heavily dependent on fossil fuels. A clean source of energy close to consumers is urgently needed. At the same time, the accelerating use of mineral resources is part of our high-tech future, not only for renewable energy technologies but also in other economic sectors. Satisfying this growing demand cannot be solved by recycling

[212] International Energy Agency. 2018. World Energy Outlook, see https://www.iea.org/weo/.

[213] World Bank. 2015. see iea.org/stats/index/asp.

alone and requires intensive exploration for those resources that can be developed the most sustainably.[214] T8 will be among the first dedicated geoscience initiatives worldwide to focus on deep resources as the solution to our future energy and raw materials supply. Realizing those solutions will require new concepts for subsurface utilization and geological storage of waste from energy production, new techniques for the discovery of subsurface mineral resources on land and in the oceans, and new observational, experimental and simulation platforms for developing novel exploitation strategies. The proposed research will take advantage of the close links between natural and engineered systems – a unique opportunity within T8 – comparing modern geothermal systems and their ancient analogs to inform the development of new, more sustainable exploration and exploitation strategies. It will explore complex interactions between the geosphere, biosphere, hydrosphere, and atmosphere that determine the occurrence and distribution of resources and energy as well as the environmental impacts associated with their development on a rapidly changing Earth. This research requires comprehensive observational approaches that include not only the direct detection of resources, but also data integration and analytics, complex time-series studies, and stronger links between field observation, use of natural laboratories, experimentation, and modeling workflows.

Strategic guidelines (FoPoZ). T8 is the essential part of the Program 'Changing Earth' that tackles the increasing use of underground geosystems, development of concepts for the exploration of primary raw materials, and assessing the potential of marine georesources and it directly addresses the research policy goals of Helmholtz and the BMBF framework 'Research for Sustainable Development (FONA3)' and the GEO:N and MARE:N initiatives. Joint expertise in deep crustal processes and geothermal energy will be applied to the problems of supplying clean and reliable thermal energy to consumers at the point of use, e.g., in urban centers. We will maintain and develop outstanding research infrastructure (underground labs, deep exploration and subsurface monitoring technologies). T8 researchers will continue, and expand, their leadership roles in international networks and our infrastructures will attract external researchers and industrial collaborators, thereby transferring critical knowledge to stakeholders. This approach will facilitate policymakers in science-based decisions about future resource utilization and management. Among the Topic outcomes will be geothermal energy development, mineral exploration for deep 'blind' deposits, and best-practice guidelines applicable to

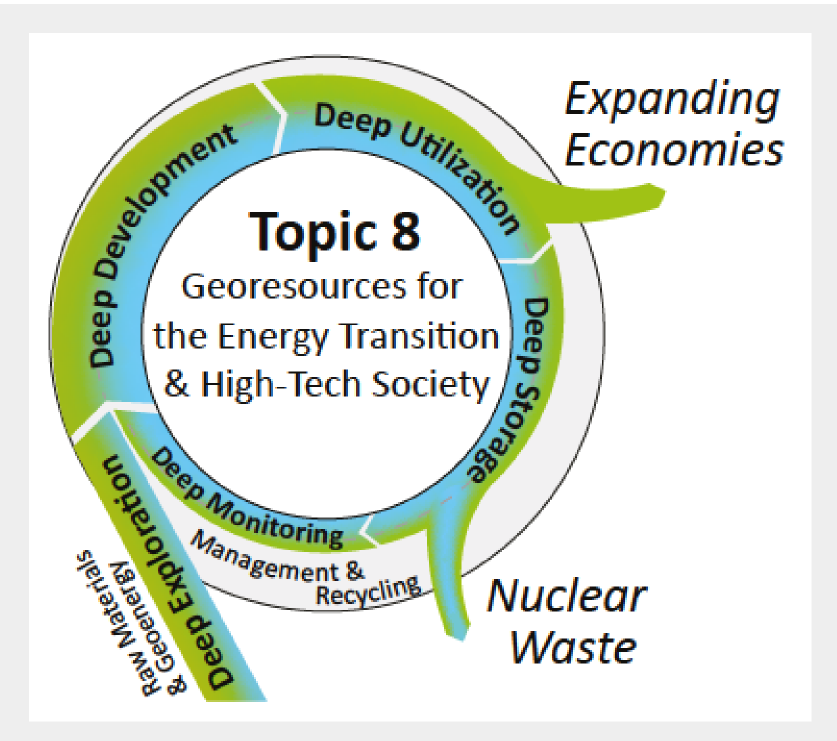


Fig. 8.1 shows the value chain of Geoenergy (blue) and Raw Materials (green) systems. The loop for Raw Materials cannot be closed due to increasing demand, and nuclear waste cannot currently be reused. The fields in grey represent linked research carried out in other Research Fields e.g. RF Energy.

[214] Ali SH, Giurco D, Arndt N, et al. 2017. Mineral supply for sustainable development requires resource governance. Nature. 543:367–372.

industry, municipalities, and the scientific community. The research data will be fully accessible in agreement with Germany's digitalization goals and embedded in Germany's national data strategy NFDI4Earth.

Function and contribution of the Topic within the Program. T8 will advance the grand challenge addressed in the Program focused on 'dwindling natural resources as a limiting factor for societal development'. To maximize our scientific contributions we are combining, for the first time, expertise in diverse areas of energy and raw materials into one Topic, embracing not only scientific knowledge on resources on the continents and deep in the Earth's crust but also in the marine environment. With this approach we will achieve an outcome that is greater than the sum of its parts and form a systemic understanding of the future availability of resources and the impact of their development on the environment. Our research data generated in laboratories, tested in the field and in underground facilities, and captured in models, will be used to develop 'real life' solutions to clean energy and resource discovery. The research in T8 links primarily to T3, T5 and T6, will contribute to the CTAs ESM and DE and is an integral part of the CARFs Resilient Urban Spaces, Geoenergy, and Nuclear Repository Research. T8 will maximize the societal impact of its research by ensuring that data are accessible and fully integrated in the RF E&E digital infrastructure, and presented both as factual information and as projected scenarios for policymakers, industry stakeholders and the general public via SynCom.

Highlights. The following highlights will be achieved in T8 in the PoF IV period.

Determining the major controls on the location and quality of future energy and raw materials resources and how we can access those resources in a sustainable way.

Integrated research on modern hydrothermal and geothermal systems and their ancient analogs, in natural and engineered systems, to quantify the key controls that lead to the formation of georesources.

B) Main research and structural objectives

Research Objectives.

- **Objective 1:** Design innovative concepts for subsurface energy utilization, storage and monitoring in the urban energy supply system.
- **Objective 2:** Advance knowledge-based approaches for the geological storage of waste from energy production.
- **Objective 3:** Identify priority targets for the future supply of mineral resources on land and in the oceans.
- **Objective 4:** Devise methods to assess the coupled thermal, hydraulic, mechanical, chemical, and biological interactions controlling the production of heat or hydrocarbons, where energy or materials may be stored, and where and when metals are deposited.
- **Objective 5:** Integrate geodynamics into georesource process models for the exploration of high-value georesources, and for defining boundary conditions for safe subsurface utilization.
- **Objective 6:** Develop new and advanced technologies for high spatial resolution detection and monitoring in the subsurface.

Structural Objectives.

- **Objective 7:** With input from stakeholders, jointly develop and apply dedicated field-based and subsurface experimental observatories, and research infrastructure for geoenergy and raw materials applications.
- **Objective 8:** Develop a management structure within the Topic to maximize interaction and knowledge transfer between centers and develop the next generation of geoscientists for careers, including those in industry.
- **Objective 9:** Incorporate research results and concepts into SynCom, and transfer knowledge to the public and policymakers. Develop and trace technology transfer to stakeholders.

C) Structure of the Topic and motivation of Subtopics

Introduction of Subtopics. Researchers from GFZ, UFZ and GEOMAR will address how the deep subsurface and oceans can be utilized to provide energy, mineral resources, and safe material storage in the framework of three Subtopics. These Subtopics will focus on the development of comprehensive models of key geoenergy (ST8.1 Geoenergy) and mineral systems (ST8.2 Raw Materials) and how they can best be utilized, including; the sources, sinks and transport pathways for material and energy flows; quantification of natural and anthropogenic variations in the systems; and new laboratory analyses and experimental constraints on the processes that govern the distribution and quality of resources in the deep crust.

A third Subtopic, ST8.3 Integrating Geoenergy and Mineral Systems, will explore the many linkages between Geoenergy and Raw Materials systems in terms of: i) the large-scale geodynamic controls on energy and mass transfer, ii) the unique physical, chemical, and biological conditions and process interactions that lead to the formation and transformation of energy and mineral resources at depth, and iii) the technological means to detect, monitor, and predict the outcome of those processes (Fig. 8.2).

The critical advance in PoF IV will be new 4D Earth modeling[215] of energy and mineral systems, which links near-surface observations to the deeper subsurface at a range of scales, from geochemical tracers of fracture-related fluid flow to regional geodynamic controls. This type of integration of geomechanical, geochemical, and geophysical data to model basin and reservoir conditions revolutionized the petroleum industry in the last decade. The integrative Earth modeling research in T8, together with new approaches to data science in the Helmholtz Association, holds the potential to similarly revolutionize the related fields of geothermal energy, subsurface storage, and mineral systems.

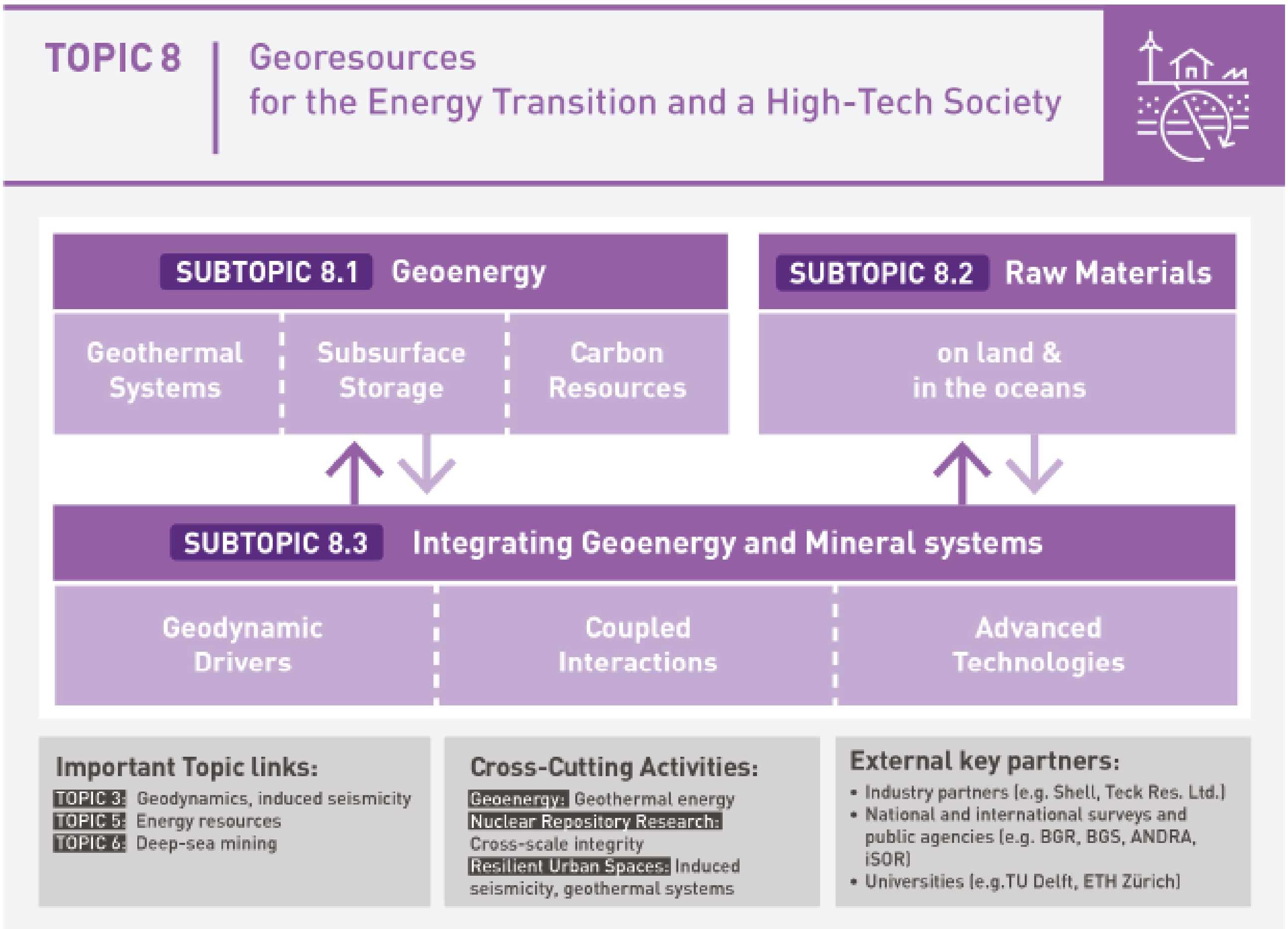


Fig. 8.2 shows the relationship of the three Subtopics.

[215] *Blöcher G, Cacace M, Reinsch T, Watanabe, N. 2015. Evaluation of three exploitation concepts for a deep geothermal system in the North German Basin. Computers and Geosciences. 82:120–129.

Contributions of the Centers to the Topic. Research at the **GFZ** is focused on the composition, structure, and dynamics of the solid Earth at human and geological time scales. In particular, GFZ contributes considerable expertise in coordinated research on geothermal energy and geological storage, including in large underground laboratories and deep crustal drilling projects, provides world-class research capacity in the fields of deep C-cycling and microbiology, and in metallic mineral resources in magmatic, hydrothermal and sedimentary systems. This includes geophysical imaging and monitoring, geochemical-mineralogical-hydrological experimentation, and 4D modeling of key processes in the subsurface. Researchers at **UFZ** have developed an open-source research platform (OpenGeoSys) for the numerical simulation of thermo-hydro-mechanical-chemical (THMC) processes in porous and fractured media, including data integration and visualization,[216] and will provide seamless workflows for the numerical analysis of coupled processes in geosystems, tailored to T8 (energy resources, storage and waste). The open-source workflow concept includes knowledge transfer elements in both directions, for education and training, for dissemination, and maintaining competence as well as gaining knowledge from the stakeholder community. **GEOMAR** investigates physical, chemical, and biological processes in the oceans that are relevant for energy and mineral resources. This involves deployment of large sea-going infrastructure for crustal imaging, detection and exploration of seafloor hydrothermal systems, and numerical modeling of heat and fluid flow in the ocean crust. Of particular importance for T8 is GEOMAR's research on marine mineral resources and active ore-forming systems at the seafloor, which are analogs for both ancient ore deposits on land and continental geothermal systems.

Critical to the success of the Topic will be the interaction between the research teams of GFZ, UFZ and GEOMAR. Scientific integration will be achieved through joint use of key infrastructure such as MESI (Ch. 14), RV Alkor (Ch. 13), sub-surface and sea-floor observatories and modeling infrastructure. The spokespeople for each Subtopic have been drawn from two centers, and will constitute a T8 management board (with other members of the writing team) to maximize communication and to respond to emerging opportunities and risks in a timely manner (see below). Integration and innovation will also be promoted by running joint workshops, short-courses and field excursions, and a dedicated annual T8 conference for students and early career researchers.

D) Subtopics

Subtopic 8.1 Geoenergy

David Bruhn, GFZ; Olaf Kolditz, UFZ

Scope and challenges. Geothermal systems, carbon resources, and subsurface storage repositories are hosted in upper crustal rocks (Fig. 8.3) and are either the products of, or are modified by, mass and energy transport processes and feedbacks. Transport properties of the upper crustal units determine the nature and accessibility of potential reservoirs and repositories. For example, in geothermal systems and during the production of hydrocarbons, stimulation treatments producing a long-term, conductive hydraulic network are required, whereas the integrity of a host rock for a nuclear waste repository requires the exact opposite i.e., low or no-flow conditions. Understanding these same processes is critical for other resources, including in mineral exploration (see ST8.2 and ST8.3). To increase the public acceptability of subsurface utilization for geoenergy, particularly in densely populated areas, stimulation treatments and other technologies associated with the circulation of the fluids need to be optimized and closely monitored to mitigate risks and minimize adverse side effects, such as induced seismicity (link to T3)[217] or drinking water contamination (link to T5).[218]

[216] *Kolditz O, et al. 2012. OpenGeoSys: an open-source initiative for numerical simulation of thermo-hydro-mechanical/chemical (THM/C) processes in porous media. Environ Earth Sci. 67 (2):589–599.

[217] *Grigoli F, Cesca S, Rinaldi AP Manconi A, López-Comino JA, Clinton JF, Westaway R, Cauzzi C, Dahm T, Wiemer S. 2018. The November 2017 Mw 5.5 Pohang earthquake: a possible case of induced seismicity in South Korea. Science. 360 (6392):1003–1006.

[218] Shortall R, Davidsdottir B, Axelsson G. 2015. Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks. Renewable and Sustainable Energy Reviews. 44:391-406.

Geothermal energy is an important domestic source for the future energy mix. ST8.1 will assess geothermal resources in the North German Basin, with a focus on application to urban areas. Our goal is to go beyond the current state-of-the-art shallow level exploitation, and to develop strategies for deep heat storage and direct heat supply. This includes the characterization and concepts for superhot geothermal sources at the roots of magmatic systems, as currently developed for the Reykjavík metropolitan region in Iceland. We will provide solutions for bottlenecks along the development chain of geothermal plants in intermediate, deep, and superhot environments. For example, hydraulic stimulation of utilized reservoirs bears the potential risk of induced seismicity, which needs to be controlled or avoided. The aim of these efforts is to determine system interdependencies to reduce the overall impacts of exploration and exploitation, and improve the market penetration of geothermal energy.

Subsurface storage will be increasingly important in renewable energy systems with fluctuating supply, which require storage of large quantities of energy (hundreds of TWh). A variety of efficient and sustainable geoscience solutions are needed to capture excess energy from renewable sources and transform it into storable fluids. The greatest potential exists in the high-energy density form of 'renewable' hydrogen, and methane synthesized from it, which can be stored at depth. The subsurface is also potentially a reliable and safe repository for heat-generating radioactive waste. Safe storage over time scales of hundreds of thousands of years requires new process understanding, experimental concepts, and simulation tools for different repository evolution scenarios in different host rocks.

A cleaner, more efficient use of **carbon resources** will be necessary during the energy transition from nuclear power and coal to renewable energies, and research in ST8.1 will focus on improving the production efficiency from conventional and unconventional systems. This will be achieved by determining the controls on fluid partitioning and the physical properties of petroleum, which influence transport, accumulation, seepage and extraction in the subsurface. This work will also include research on gas hydrates, a potential source of natural gas. It will also focus on the geomechanical and physical properties of hydrate-bearing sediments, a risk for slope stability, which links to research in T3.

Main objectives and Work program. Our objectives are to develop quantitative 4D models of the physical properties and processes of both natural and engineered systems that will allow optimal design for energy provision and storage in the deep underground. The emphasis of the work program will be on the challenges and opportunities in securing a reliable, economically efficient, and environmentally friendly energy mix to support the energy transition.

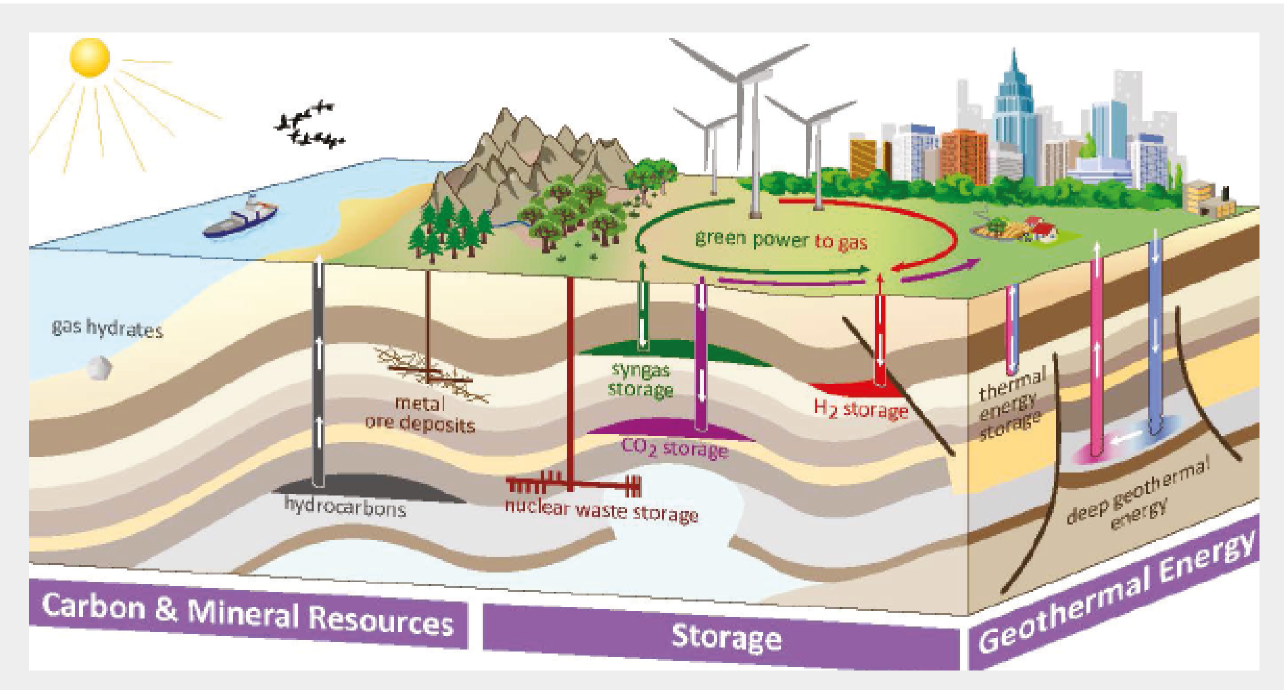


Fig. 8.3: Conceptual use of the subsurface in Topic 8.

Geothermal Energy. In ST8.1 we aim to provide the geothermal solutions for thermal energy provision in cities (heating and cooling), and to constrain the key processes necessary for the exploitation of intermediate depth, deep, and superhot geothermal systems. This will entail fundamental conceptual advances in process quantification to develop best-practice scenarios for sustainable exploitation. The critical issues of fracturing in the brittle-ductile regime and geochemical feedback loops will be investigated, taking into account site-specific geomechanical, geochemical, and microbiological conditions.[219] This will form the basis for developing optimized production strategies and minimizing the induced hazards associated with reservoir stimulation (link to ST8.3 and T3) – a vital issue when considering geothermal usage in metropolitan areas. Another unresolved problem for efficient geothermal energy production is scaling, the precipitation of minerals in geothermal wells, which has many parallels in mineralizing systems (link to ST8.2).

We will focus our research on performance enhancement for urban areas in various geological settings, including deep sedimentary basins[220] and volcanic regions (link to RF Energy). In particular, we will demonstrate safe and reliable heat recovery from deep, hot, and highly saline reservoirs from the North German Basin. We will also characterize and develop concepts for exploitation of at least one superhot geothermal system, e.g., in Iceland or Mexico. We will aim to optimize reinjection temperatures for the different geothermal systems at different depths, hydraulic, and temperature regimes to inhibit scaling problems, comparing the results with fossil hydrothermal systems. In order to provide and test practical solutions to these issues it is essential to scale up laboratory experiments and models in demonstration sites. This long-term work involves the development of productivity-enhancement concepts for different rock types, e.g., our underground research facility Groß Schönebeck (GFZ), or the superhot test sites in Iceland (linked to geodynamic research in the region in T3) via the Iceland Deep Drilling Project.

D8.1 (2027): Deliver a proof of concept for urban geothermal heat provision from greater depths. **M8.1-1 (2022):** Assess the geothermal potential beneath urban areas (link to CARF Resilient Urban Spaces). **M8.1-2 (2024):** Develop a concept for the integration of geothermal utilization in urban heating and cooling. **M8.1-3 (2026):** Demonstrate safe and reliable heat recovery from deep, hot and highly saline reservoirs for urban energy supply. **M8.1-4 (2026):** Characterize and develop a concept to access at least one superhot geothermal system.

Subsurface Storage. In ST8.1 we will leverage the experience from carbon capture and storage research (e.g., Ketzin pilot site)[221] in the North German Basin, and transfer this knowledge to other types of gas, energy, and nuclear waste storage. Linked to our research in geothermal energy, utilization strategies will also be tested for heat storage and cooling from intermediate depths, a significant step beyond the current state of the art. We will determine efficient and sustainable approaches to store excess energy in the form of fluids (e.g., hydrogen and synthetic gas) by power-to-gas conversion (link to T7) to address the issue of fluctuating energy provision. This will include carrying out geochemical and petrophysical experiments to improve the modeling of the key processes.

The safe, reliable storage of Germany's nuclear waste also requires a long-term research perspective on the processes that control the integrity of potential host rocks. It has not yet been decided what type of repository could be developed (e.g., in rock salt, clay-rich units or crystalline rocks), and fundamental physical, chemical and biological data relevant to the different host rocks are needed that we will generate from experiments and laboratory analyses. Access to the Mt Terri underground lab and other scientific infrastructure means researchers from GFZ and UFZ are ideally suited to address the issues of scaling up to a full-sized facility and the assessment of far-field effects e.g., thermo-hydro-mechanical coupled processes (link to RF Energy, CARF Nuclear Repository Research) to enable science-based decisions to be made on the final site selection.

D8.2 (2027): Establish multidisciplinary scientific research platforms offering geoscience solutions to energy storage and safe disposal of radioactive waste in the subsurface. **M8.2-1 (2022):** Assess the potential of various

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[219] *Regenspurg S, Alawi M, et al. 2018. Impact of drilling mud on chemistry and microbiology of an Upper Triassic groundwater after drilling and testing an exploration well for aquifer thermal energy storage in Berlin (Germany). Environmental Earth Sciences. 77:516.

[220] *Kastner O, Sippel J, Zimmermann G. 2015. Regional-scale assessment of hydrothermal heat plant capacities fed from deep sedimentary aquifers in Berlin/Germany. Geothermics. 53: 353–367.

[221] *Martens S, Kempka T, Liebscher A, Lüth S, Möller F, Myrttinen A, Norden B, Schmidt-Hattenberger C, Zimmer M, Kühn M, The Ketzin Group. 2012. Europe's longest-operating on-shore CO_2 storage site at Ketzin, Germany: a progress report after three years of injection. Environ Earth Sci. 67:323–334

storage scenarios for excess renewable energy in the North German Basin. **M8.2-2 (2024)**: Develop a concept for waste storage and a combined storage and usage option for fluids. **M8.2-3 (2026)**: Implement underground storage including integration of recovered liquids and/or gas into an existing distribution infrastructure. **M8.2-4 (2026)**: Evaluate long-term safety issues of nuclear waste disposal in clay, crystalline units or rock salt.

Carbon Resources. To support the Energy Transition, our research in hydrocarbons will focus on improving the efficiency of production and reservoir management. Within our hydrocarbon and gas hydrate research, the interaction processes of deep organic fluids or hydrate phases with the host rock matrix, formation waters, and microbial communities are of central interest. We will also determine the molecular compositions of the deep organic fluids, including polar compounds, and link those with their physical properties and fluid dynamics, which are crucial for efficient exploitation and management concepts including minimizing environmental impacts.

D8.3 (2027): Improve the efficiency of exploitation strategies by quantifying hydrocarbon fluids and gas hydrates properties from their molecular compositions. **M8.3-1 (2024)**: Assess and quantify the impact of fluid-rock, organic-inorganic, and microbial interactions on the composition of hydrocarbons. **M8.3-2 (2024)**: Determine the geo-mechanical properties and seismic wave velocities of gas hydrate-bearing sediments (link to T3). **M8.3-3 (2027)**: Generate models predicting hydrocarbon fluid and gas hydrate properties based on compositional molecular parameters.

Subtopic 8.2 Raw Materials

Sarah A. Gleeson, GFZ; Mark Hannington, GEOMAR

Scope and challenges. New sources of metals for the energy transition and high-tech society are required for the development of metal-intensive 'green technologies' and to support our growing energy infrastructure. The major commodities that will drive the energy transition are the strategic (e.g., Cu, Zn) and critical metals (e.g., Rare Earth Elements (REE), W, Co). To address the demand for these metals, research must be focused on identifying resources that can make a substantive contribution to supply. To ensure long-term resource security, those resources must be found before they are needed (e.g., avoiding such events as the REE crisis of 2010). The long lead times for sustainable resource development must be eliminated, and unconventional resources that have the potential to have a very large impact on supply (e.g., black shale-hosted deposits or phosphorites) should be identified. Unlocking the Earth's deep and unconventional resources has the potential to dramatically increase global raw material security. On land, the challenge is to discover deeply-buried, high-value mineral resources on which future supply security will depend. In the oceans, the challenge is to establish what seafloor resources (sulfides, Mn-nodules) can realistically contribute to global metal supply, taking into account the potential impact on the environment if they are developed (links to T5 and T6).

Main objectives and Work program. Our major task is to identify and characterize the large mineral systems that will have the greatest impact on our future and to generate the fundamental data for targeting those high-value deposits at depth. The main focus is to identify the conditions that maximize metal fluxes in different mineral systems and thereby contribute to the formation of the largest deposits. We will build the next generation of mineral system models incorporating new physical-, chemical-, and thermal controls on metal sources, sinks and transport pathways, taking into account the regional space/time variations imposed by different geodynamic settings and placing new constraints on the processes that govern resource distribution. We will focus on three broad groups of deposits that are likely to contain the vast majority of tomorrow's strategic and critical mineral resources. These include magmatic deposits in intrusive complexes, magmatic-hydrothermal deposits in continental margin settings, and massive sulfide deposits hosted by volcanic and sedimentary rocks in sedimentary basins and on the seafloor (Fig. 8.4). A key aspect of the research will be direct comparisons with natural and engineered geothermal systems and their derived models and experimental results in ST8.1.

Magmatic deposits related to mafic-ultramafic, alkalic-carbonatitic and felsic-pegmatitic intrusions provide much of the world's Cr-Ni-PGE (platinum-group elements), REE, and Li-Nb-Ta supplies. The different metal associations relate to the type of magma (source), but we have no criteria to distinguish barren from mineralized intrusions because the metal enrichment processes are poorly known (e.g., melt formation and segregation, liquid immiscibility and volatile saturation vs. crystallization). Research in ST8.2 will combine geochemical/

isotopic tracers of magma source and evolution with experiments that determine how metals behave during melting and crystallization. One focus area will be on large igneous provinces that are thought to contain the largest proportion of the world's undiscovered resources of this type; in particular, the Bushveld Complex in South Africa (70% of global PGE reserves) and analogs in the North Atlantic (e.g., Iceland, E. Greenland).

Magmatic-hydrothermal deposits in subduction and collisional zones (e.g., Andean and Variscan belts) are major suppliers for Cu, Mo, Au, Ag, Sn, and W. Quantifying the processes of generation, emplacement, and degassing of fertile magmas in these systems and identifying the mechanisms of focused fluid flow and ore precipitation by physical and chemical fluid-rock interactions are key to guiding future exploration. Fundamental processes that will be addressed include the importance of pre-enrichment in source areas for melt generation, the manner of volatile release from incrementally growing magmatic intrusions, and the role of fault structures in dynamic ore-forming hydrothermal systems.

Massive sulfide deposits in volcanic and sedimentary basins, such as the North German Basin, have the potential to host significant Cu, Zn, and Pb resources. Research on this group of deposits will combine contributions from GEOMAR on active marine systems with work by GFZ researchers on ancient analogs now on land. We will study the interactions of diagenetic and hydrothermal processes[222] coupled to the 4D evolution of permeability and porosity that govern heat and fluid flow in these systems. This research is directly analogous to the study of reservoir evolution and characteristics in ST8.1. In low-temperature systems, the role of biotic communities and organic material in metal enrichment and deposition is a key aspect. We will apply organic geochemistry techniques to ore deposits for the first time (e.g., Fourier Transform Ion Cyclotron Resonance Mass Spectrometry) to assess the role of organic matter in S cycling and in the transport/precipitation of redox-sensitive metals. Marine minerals are increasingly viewed as part of the future resource spectrum; however, for most deep-sea resources there is a lack of detail on deposit characteristics and a corresponding low confidence in resource estimations. We will apply the mineral systems approach to find new ways to explore for massive sulfide systems beyond the currently-known active neovolcanic zones of the mid-ocean ridges, including in volcanic basins related to subduction zones in the Western Pacific, and we will examine the potential for nodules beyond the Clarion Clipperton Zone (CCZ) license area in the Central Pacific.

In each of these areas we will address why specific combinations of critical and strategic metals occur together and which processes control the 4D distribution of different elements from the regional scale to the district and deposit scales. These processes leave distinct chemical and mineralogical 'footprints' that can be used for detection of hidden resources but are also important for quantifying potentially negative downstream behavior following exploitation (e.g., release of toxic metals to the environment, link to T5). Complementing this research, we will design laboratory analyses and experiments to place new constraints on metal mobilization, transport, and deposition, and to inform the integrated system models developed in ST8.3. Our data from case studies and experiments will also provide necessary input for technical solutions for efficient metal extraction from natural ores and for development of new materials for green technology (links to RF Energy and RF Matter, respectively), and for problems such as mineral scaling in geothermal systems (see ST8.1).

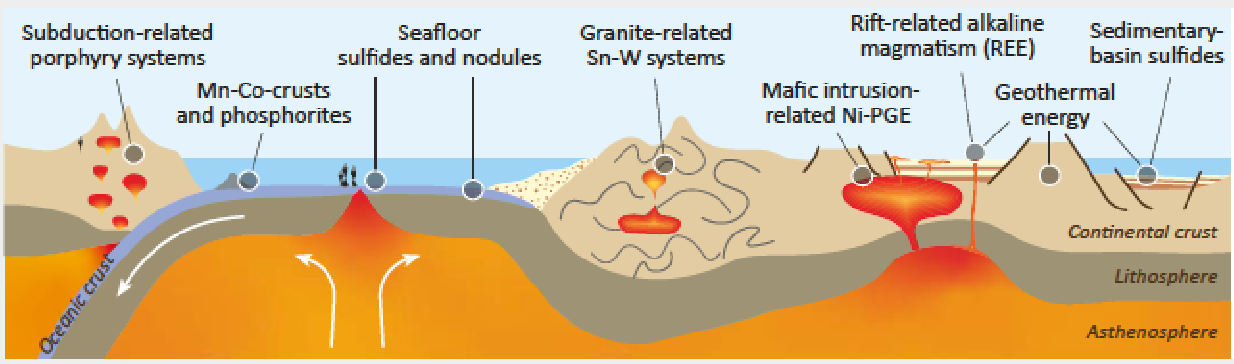


Fig. 8.4: Some key geodynamic settings of mineral deposits and geothermal systems.

[222] *Magnall JM, et al. 2016 Open system sulphate reduction in a diagenetic environment - Isotopic analyses of barite and pyrite from the Tom and Jason, Late Devonian, Zn-Pb-Ba deposits, Selwyn Basin, Canada. Geochimica et Cosmochima Acta. 180:146–163.

- **D8.4 (2027):** Build comprehensive new mineral systems models for critical and strategic metals on land and in the oceans. **M8.4-1 (2023):** Quantify the concentration and distribution of metals in the crust and identify their sources and transport pathways. **M8.4-2 (2024):** Quantify the controls on critical and strategic metals distribution in terms of magmatic, hydrothermal, or biological processes. **M8.4-3 (2026):** Design new laboratory analyses and experiments to place constraints on metal mobilization, transport, and deposition to verify the system models.

Subtopic 8.3 Integrating Geoenergy and Mineral Systems

Mark Hannington, GEOMAR; Magdalena Scheck-Wenderoth, GFZ

Scope and challenge of the Subtopic. Strong synergies exist between the ST8.1 Geoenergy and ST8.2 Raw Materials because essentially the same processes and interactions control the distribution of energy and metal resources in the Earth system and because the research approaches in both fields are highly complementary (Fig. 8.5). For example, geothermal energy infrastructure provides samples of deep hydrothermal fluids[223] that are direct analogs for ore-forming fluids in ancient magmatic and hydrothermal systems. Ancient ore-forming systems record the long-term effects of fluid-rock interaction, which provide important constraints on aspects of geothermal energy production (e.g., scaling in geothermal wells) and the search for safe, long-term repositories for energy or radioactive waste (e.g., development of fractured reservoirs).

We have identified three key areas where integration of research in ST8.1 and ST8.2 has the potential to make significant contributions to both fields: i) identifying geodynamic and structural controls on the distribution of energy and raw materials in the crust, including natural variations on geological time scales, ii) identifying the unique combinations of physical, chemical, and biological processes that control the formation of both energy and raw materials, and iii) developing next-generation technologies for the detection, delineation and monitoring of those resources (Fig. 8.5).

Main objectives and Work program.

Geodynamic Drivers of Energy and Mineral Systems. The major driver of energy and mass transfer in the Earth's crust is plate tectonics. ST8.3 will explore these regional-scale controls on georesource distribution, based on studies of the geodynamic settings of different energy and mineral systems in a 4D framework (links to T3). New research will include geophysical imaging experiments to identify crustal architecture and fault systems[224] that control melt and fluid pathways and thereby provide a framework for integrating plate-boundary processes (magmatism, deformation, uplift and sedimentation) into mineral and energy system models. Examples where this research can be combined to include geothermal energy, storage potential, carbon resources and active metal-depositing hydrothermal systems are found: i) in the intracontinental basins of North-Central Europe, ii) in the foreland basins of the Andes and Alps, iii) in young rift systems in Europe and East Africa, iv) marginal basins of the western Pacific, and v) in large igneous provinces such as in South Africa and East Greenland/Iceland. For example, the capacity of large-scale sedimentary basins for ore formation, geothermal energy, and storage of mineral and energy wastes is directly linked to their geodynamic history, including far-field and near-field stresses, thermal regimes, and the development of heterogeneous physical rock properties. To quantify these aspects requires new efforts to determine the physical properties of the rocks, minerals, and fluids and their responses to long-term (geological) and shorter-term (partly induced) stresses. These data are also critical for assessing potential risks in different systems, e.g., induced seismicity in response to reservoir utilization,[225] thermal variation, and the long-term stability of repositories for nuclear waste. In geothermal systems, for example, a major focus is to support development of mitigation strategies for hazards caused by anthropogenic stress and thermal changes (link to T3 and RF Energy).

[223] *Hannington M, Hardardottir V, Garbe-Schonberg D, Brown K. 2016. Gold enrichment in active geothermal systems by accumulating colloidal suspensions. Nature Geoscience. 9(4):299–302.

[224] *Geersen J., et al. 2018. Active tectonics of the North Chilean marine forearc and adjacent oceanic Nazca Plate. Tectonics. 37: 4194–4211.

[225] *Kwiatek G, Saarno T, et al. 2019. Controlling fluid-induced seismicity during a 6.1 km deep geothermal stimulation in Finland. Science Advances. (5) 5:eaav7224.

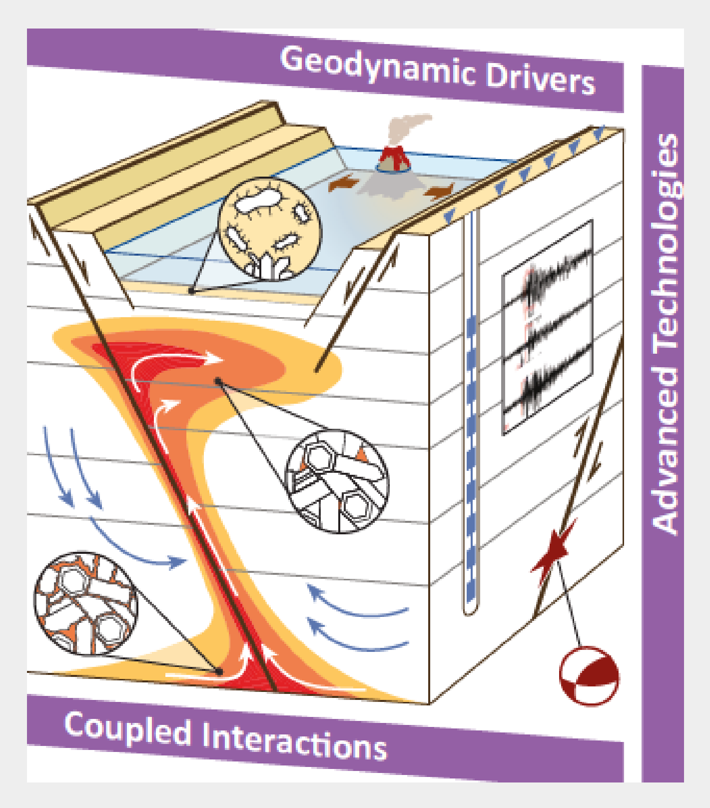


Fig. 8.5: Research in ST8.3 will focus on modeling coupled processes and applying new technologies for the detection and monitoring of georesources.

Coupled Interactions in Energy and Mineral Systems. Both energy and mineral systems involve complex coupling of THMC processes acting over a large range of temporal and spatial scales. There is increasing evidence that feedbacks among these processes create thresholds or tipping points that may determine the evolution of the systems. Conventional models consider these interactions individually, with little capacity for analyses of coupling, feedbacks or cascading effects. ST8.3 will focus precisely on these effects (Fig. 8.5), including the role of organic-inorganic and microbial interactions, which can be particularly important for the formation of mineral and energy resources in sedimentary basins, and for developing strategies for energy production and storage potential. The role of microbiological processes, organic matter, and organic geochemistry in mineral dissolution, precipitation and mass transfer is still poorly understood and research groups at GFZ, UFZ and GEOMAR are ideally positioned to be leaders in this field[226] (link to T5 and T6). A particular emphasis will be direct measurements of microbial activity using multi-omics approaches (genomics, transcriptomics, lipidomics, proteomics) and metabolic network modeling (link to T5 and T7).

A major challenge for ST8.3 will be the integration of diverse datasets and conceptual knowledge of geoenergy, storage potential, and mineral resource formation into more comprehensive system models. Robust THMC modeling tools are currently being developed at all centers for application to geothermal energy, geological storage of energy and fluids, nuclear waste disposal, and mineral resources. A core component of the modeling is reactive transport and permeability evolution in sedimentary and crystalline rocks. These models accommodate variables of pressure, temperature, rock permeability, regional heat- and stress fields, mineral solubilities, and compositional data on volatiles and fluids, across a range of temporal and spatial scales. ST8.3 will advance this research toward an open, modular simulation framework that adds process coupling and interactions among physical, chemical and microbiological components, and their response to drivers in the local and broader geodynamic framework of energy and mineral systems. A strong collaboration with the NUSAFE project (RF Energy) will be established for models of the nuclear waste storage systems, with particular focus on aspects of radiochemistry and radioecology.[227]

[226] *Vetter A, Mangelsdorf K, Wolfgramm M, Rauppach K, Schettler G, Vieth-Hillebrand A. 2012. Variations in fluid chemistry and membrane phospholipid fatty acid composition of the bacterial community in a cold storage groundwater system during clogging events. Applied Geochemistry. 27:1278–1290.

[227] *Yang S, Schulz H, Horsfield B, Schovsbo NH, Noah M, Panova E, Rothe H, Hahne K. 2018. On the changing petroleum generation properties of Alum Shale over geological time caused by uranium irradiation. Geochimica et Cosmochimica Acta 229:20–35.

- **D8.5 (2027):** Establish integrated modeling of energy and mineral systems for comprehensive georesources management and applications. **M8.5-1 (2024):** Tie regional geodynamics to mineral and energy systems in a 4D framework (link to T3). **M8.5-2 (2024):** Determine physical properties of rocks, minerals, and fluids and their response to geological and anthropogenic stress changes. **M8.5-3 (2026):** Develop strategies for minimizing exploration or production-induced hazards, including stress- and thermal changes (link to T3 and RF Energy). **M8.5-4 (2026):** Integrate coupled processes of fluid-rock interaction, including those related to the deep biosphere, into models for geoenergy, subsurface storage, and mineral systems. **M8.5-5 (2027):** Build an open, modular simulation framework capable of addressing the complexity of coupled interactions among the physical, chemical, and microbiological components of energy and mineral systems.

Advanced Technologies for Analysis and Discovery. In the next decade, resource discovery and utilization at depth will require new, sophisticated, technologies and instruments to extract maximum value from the resources and to safeguard against the negative impacts of exploitation. In ST8.3, we will advance technological applications on several fronts. For example, fiber-optic distributed acoustic sensing (DAS), which was recently developed for real-time monitoring during geothermal well construction, injection, and production, as well as for imaging the shallow subsurface,[228] will be further developed for new applications in geothermal exploration and monitoring of the urban underground. We will also test the application of this technology in geodynamics research, mineral exploration, and in development and monitoring of nuclear waste repositories (link to T3 and CARF Nuclear Repository Research). GEOMAR and GFZ will jointly develop multi-parameter sensor systems (seismic, magnetotelluric, geochemical) for exploration, assessment, and monitoring of deep geothermal and mineral resources in different geological settings and lithologies. This includes developing a comprehensive method for core-log seismic integration (link to T3). We will continue to develop, seafloor observation platforms for use in integrated study sites, including ocean floor geophysical observatories for the detection of concealed seafloor massive sulfide deposits.[229]

Advanced technologies for testing in analytical and experimental laboratories on-site and in the field will be core elements of ST8.3 (see infrastructure section below). The capability and expertise in geological, mineralogical and geochemical analysis extends from the nanoscale to entire geoenergy and mineral systems, and involves both empirical field and laboratory studies as well as extensive experimentation with model systems that can also simulate the downstream impacts of resource utilization, (e.g., the Large Scale Reservoir Simulator at GFZ and unique high-pressure flow-through reactors at GEOMAR). A particular strength of the UFZ-GEOMAR-GFZ collaboration is the capability to integrate new multi-scale and multi-sensor instrumentation such as multi-scale seismic and geoelectric methods (collaboration with T3) that will be tested in underground research labs and at the seafloor. Among the applications of these methods are the exploration and site characterization of prospective clay units, crystalline rocks, or salt for nuclear waste repositories.

Evermore complex observation systems will also require new concepts for data management and exploitation using advanced data science. Numerical modeling is now an integral part of the exploration workflow in geoenergy and mineral systems. Geological constraints, however, are rarely complete, and system models can have large uncertainties. Modern data-science approaches attempt to overcome this by training models in well-explored areas to make predictions in under-explored areas. However, new generations of artificial intelligence (AI) and machine learning are needed to link physical models with theoretical constraints (e.g., thermodynamic equilibria). Deep neural networks are a promising way forward as they can handle spatio-temporal dependencies, including variations in the state of the system in addition to local environmental conditions.[230] Testing the reliability of these tools and approaches will be of critical importance in the next decade, as we are required to provide confidence limits on different aspects of subsurface energy and mineral systems for the safe design of usage options of the subsurface. Sensitivity tests can assess model reliability, but increasing the reliability

[228] *Jousset P, et al. 2018. Dynamic strain determination using fibre-optic cables allows imaging of seismological and structural features. Nature Comm. 9:2509.

[229] *Safipour R, Hölz S, Halbach J, Jegen M, Petersen S, Swidinsky A. 2017. A self-potential investigation of submarine massive sulfides: Palinuro Seamount, Tyrrhenian Sea. Geophysics. 82:A51–A56.

[230] Reichstein M, Camps-Valls G, Stevens B, Jung M, Denzler J, Carvalhais N, Prabhat. 2019. Deep learning and process understanding for data-driven Earth system science. Nature. 566:195–204.

requires identifying the key variables driving uncertainty, which can be targeted in experiments and analyses to provide better model constraints. Improving prediction quality will also require upscaling to account for process interactions in larger volumes of the crust.

- **D8.6 (2027):** Implement next-generation high-resolution (spatial and temporal) technologies for exploration and monitoring the subsurface. **M8.6-1 (2022):** Develop fiber-optic DAS for geothermal applications in the urban subsurface and for application in mineral exploration, subsurface storage and radioactive waste repositories (link to T3). **M8.6-2 (2022):** Build and test multi-parameter sensor systems for exploration and monitoring of deep energy and mineral resources. **M8.6-3 (2024):** Apply advanced data science concepts for data management/exploitation and for complex systems modeling. **M8.6-4 (2026):** Upscale predictive models for energy and mineral resources to larger volumes of the crust.

Infrastructures and specific resources for the Topic. Our strategy is to maintain and develop world-class research infrastructures and expertise in the contributing Helmholtz centers and to apply them in a multi-disciplinary and integrated way. Our subsurface and oceanic research laboratories offer an exceptional opportunity to quantify key processes, scale up our experimental data, run test simulations, and develop new monitoring techniques. In particular, we design and operate the subsurface labs needed to address the challenges of the Topic. Researchers will have access to deep geothermal boreholes in Berlin and in Groß Schönebeck, and, through international co-operation, to superhot geothermal infrastructure in Iceland, Mexico, and Japan. The Swiss underground research laboratory at Mt Terri provides an excellent basis for collaborative, multi-scale studies on clay as a host repository for nuclear waste. Access to subsurface research labs in crystalline rocks (KTB deep boreholes, Reiche Zeche research mine by TU Freiberg) will allow fundamental advances to be made in stimulation technologies to improve reservoir productivity, in the testing of multisensor systems, and in experiments on rock properties relevant to heat and fluid flow in energy and ore-forming systems. In addition, we are developing seabed geological mapping techniques and several areas have been identified as integrated study sites and testbeds dedicated to technology development for exploration of seafloor minerals. We are involved in developing the next generation of underground labs, e.g., the proposed GeoLaB with RF Energy. Global monitoring and remote sensing infrastructure based on airborne and satellite-based platforms are available for T8 from GFZ, DLR and international partnerships. These include gravity field (GRACE-FO) and hyperspectral data (EnMAP) which have applications for alteration mapping in large-scale, near-surface geothermal and mineral systems.

World-class experimental rock physics, geochemistry, and mineral synthesis laboratories at GFZ investigate processes and properties at the elevated pressures and temperatures encountered in the crust. GFZ, UFZ and GEOMAR also have state-of-the-art inorganic and organic geochemistry laboratories including isotope analysis and geochronology. GFZ operates modular infrastructure (MESI) including Europe's largest geophysical instrument pool and sophisticated micro- and nano-analytical instruments, which are partly dedicated for collaboration with outside partners. This will complement deep crustal imaging using various seismic methods, controlled source electromagnetics, and access to the global seismology network (including GEOFON) for imaging the lithospheric structure on plate scale. GFZ, and the ICDP Operational Support Group, conducts research and development in drilling technologies for imaging and sampling crustal rocks, including new down-hole tools and improved multi-parameter drill-core scanners. Finally, GFZ has established a new facility for geomicrobiological research that will enable joint studies with GEOMAR on the deep C-cycle and role of microbial activity in energy and minerals systems.

Research on marine georesources in T8 is supported by state-of-the-art infrastructure and observation platforms (ROVs, AUVs, landers, crawlers, in situ laboratories) at GEOMAR. Unique seabed mapping and sampling capabilities, including technology for direct detection of resources using seafloor magnetics, electromagnetics, redox potential, and heat flow have been established. T8 will also have access to one of the largest ocean-bottom seismometer pools available worldwide, as well as novel ocean bottom magnetotelluric instruments and the GeoSEAs array of ocean-bottom GPS network.

To support modeling and digitalization in T8, GFZ and UFZ will pool their existing modeling platforms (OpenGeoSys, GOLEM, and LYNX) and jointly develop new platforms in an open-source environment. A special contribution of UFZ and GEOMAR is the high-end visualization laboratories for interactive analysis of data and simulation workflows. For simulations of ore-forming processes, GFZ and GEOMAR are further improving state-of-the-art software for multi-phase flow of saline hydrothermal fluids below and up to magmatic temperatures in conjunction with rock mechanics (CSMP++, HT2_salt). One focus of model developments will be on feedbacks between magmatic accretion of oceanic crust, hydrothermal fluid flow, and seawater-rock-sediment-organic interactions.[231]

Risks and Opportunities for the Subtopics. T8 must be responsive to rapidly changing societal needs and also to the conditions of a changing Earth and its climate system. This includes examining the resilience of such solutions to disruption due to extreme weather and longer-term climate impacts. Risks from climate change include drought-related lowering of groundwater levels and salinization of groundwater due to sea level rise, both with negative impact on shallow geothermal and energy storage; destabilization of gas hydrates by global warming (e.g., permafrost melting in the Arctic, links to T5); and infrastructure damage from flooding. For metal mining, vast amounts of fresh water are needed for exploitation (ore treatment) and waste management (e.g., stabilization of tailings). At the same time, we believe that new opportunities for research will emerge, including new geothermal power options in underdeveloped nations or unexpected discoveries of new resource potential in areas that could change the focus of our research. All of these effects are happening now, but their societal impact and mitigation options cannot be properly assessed without a clear understanding of where our energy and raw materials will be sourced in the future.

On the Subtopic level, unforeseen events may impact the planned milestones and deliverables such as operational risks, particularly for drilling projects. However, the combined experience and research infrastructure of the partners gives considerable flexibility and this risk can be minimized by participating in several projects and cooperation with different (industry) partners, such that the overall Topic goals are met despite individual, site-specific delays.

E) Previous achievements of the contributing centers and infrastructures

Expertise and preliminary work. GFZ and UFZ have jointly developed new strategies for the use of geothermal energy during PoF III together with partners at KIT in the RF Energy. Work in PoF III resulted in the first binary geothermal power plant in Indonesia, with 100 MWh of electricity generated. Technologies for improving deep geothermal reservoir engineering focused on the research platform at Groß Schönebeck but benefited from other sites in Europe, Oman, China and Mexico. In collaboration with UFZ, GFZ successfully demonstrated the full life-cycle of subsurface CO_2 storage at Ketzin and received the first Carbon Sequestration Leadership Forum award. Extensive research on petroleum systems at GFZ laid the foundation for new work towards a more efficient utilization of fossil fuels and for assessing the effects of the deep biosphere on georesources exploitation. GFZ researchers constructed new models coupling hydrothermal flow behavior, rock mechanics, and mineralization for intrusion-related Sn-W deposits. UFZ has pioneered open-source workflows for numerical simulation of THMC processes in fractured porous media with various geoenergy and storage applications. During PoF III, raw materials research at GFZ has shown that previously-neglected processes such as electrochemical transport can play an important role in upgrading PGE in magma chambers and that large Zn deposits can form below the surface in marine sediments during early diagenesis.

In PoF III, researchers at GEOMAR and GFZ collaborated to document and model offshore hydrocarbon systems and their seepage and the CO_2 storage potential in the seabed, including technological and risk analysis. This research is now being used to understand the formation and reactivation of leakage structures relevant to storage and abandoned oil and gas production sites. GEOMAR and GFZ also jointly developed geophysical techniques for methane hydrate exploration and modeling approaches for assessing hydrate resource and storage potential in the project SUGAR (Submarine Gas Hydrate Reservoirs). The GEOMAR-coordinated research program SFB754 'Volatiles and Fluids in Subduction Zones' in Central America and Chile laid the foundation for research on the geodynamic controls of georesources in subduction zones in T8. GEOMAR research

[231] *Hasenclever J, Theissen-Krah S, Rüpke LH, Morgan JP, Iyer J, Peterson S, Devey CW. 2014. Hybrid shallow on-axis and deep off-axis hydrothermal circulation at fast-spreading ridges. Nature. 508:508–512.

on marine mineral resources has contributed extensively to the current regulations for exploration of nodules and sulfides by the International Seabed Authority (ISA). This work is also informing the exploration strategies of the Federal Institute for Geosciences and Natural Resources (BGR) in their offshore exploration licenses in the CCZ and Indian Ocean. GEOMAR also leads the EU Joint Programming Initiative (JPI Oceans) on 'Mining Impacts' (until 2022), which is studying real-time impacts of an industrial-scale mining trial for nodules.

Uniqueness. T8 will unite geothermal reservoir scientists, geophysicists, ore deposit geologists, mineralogists, organic and inorganic geochemists, and modelers in integrated studies of future geoenergy and raw material resources. By combining the study of natural and engineered systems, including modern hydrothermal and geothermal systems and their ancient analogs, we will provide unique solutions to the problem of resource supply for the energy transition, and for assessing and monitoring the impacts of developing deeper resources. The three Helmholtz centers involved have developed process-oriented research that combines specialization in crustal fluid circulation, mineral deposition, the role of geodynamic factors, and advanced THMC modeling of coupled interactions. All three centers have specialist infrastructure and expertise in utilizing natural laboratories, including drilling active hydrothermal systems on land and at the seafloor, and in using underground research facilities for long-term observations needed to up-scale laboratory results to real-world conditions. In T8, we will actively develop and design the platforms for future energy and raw materials production from ancient volcanic and sedimentary basins, and we are studying the modern analogs that hold the keys to their formation. The innovation potential of the Topic is the combination of research teams that traditionally have worked apart and the opportunity to maximize knowledge and technology transfer in a new way.

F) Collaboration and transfer

Partners. T8 is dependent on the engagement of stakeholders who are directly involved in designing the research targets, implementing new technologies, and integrating research outcomes in their decision-making and business operations. These include industry partnerships in new technology developments (e.g., Lundin, Shell, and DEA as partners in the core-log seismic integration initiative), in geothermal developments in Germany (Gasag, Innogy, Vattenfall), and in mineral resource exploration (Teck Australia plc, Mount Isa Mines, Anglo American, G.E.O.S. Freiberg, Saxore Bergbau).

Long-term international partnerships are established with academic (TU Delft and TNO Netherlands, Cornell University, ETH Zürich) and public agencies (e.g., BRGM in France, ÍSOR in Iceland, and CNR-IGG in Italy). T8 researchers are also members of the Deutsche Allianz für Meeresforschung (DAM), which supports joint research on the sustainable management of the oceans. Our numerical models for safe and sustainable subsurface storage are being benchmarked for performance and safety assessment (DECOVALEX project) with BGR, BGS (UK), ANDRA (France) and ENSI (Switzerland) and we have close collaborations with other surveys and agencies in Germany e.g., Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg and the German Environment Agency (UBA).

All of the centers participate in training the next generation of researchers as outlined in Ch. 1.4.5; however, in T8 we also aim to optimize their opportunities for employment in the georesources industries. Many of our students are funded by third-party projects with industry links. For example, at GFZ, carbon resource students participate in the Industry Partnership Program (IPP), which brings together academic and industry partners, geological surveys and other research institutions worldwide to access funding, data and samples for research. Opportunities for collaboration in raw materials research with German universities will greatly advance due to the newly-established DFG priority program 'Dynamics of Ore-Metals Enrichment'.

Positioning of the Topic in international research. T8 will be one of the few national or international programs worldwide with an exclusive focus on deep georesources in both natural and engineered systems and active and ancient geoenergy and mineral systems. The technical expertise and theory developed in the Topic and combined across a range of observational platforms and experimental frameworks with unique modeling capabilities will be a one-of-a-kind program in the terrestrial and marine sciences. It will build on existing leadership roles in such organizations as the European Energy Alliance and the European Technology Platform on Deep Geothermal Energy in several EU-projects (I-GET, GEISER, SURE, DESTRESS, as well as collaboration with Mexico in GEMex), as active partners in the European Joint Research Program for the management and disposal of radioactive waste (EURAD), and the International Continental Drilling Program (ICDP) for which GFZ leads the Operational Support Group. Both GFZ and GEOMAR are active in the International Ocean Discovery Program (IODP), and GEOMAR also provides significant input for information and outreach projects of the International Seabed Authority (ISA), UNEP and OECD on marine resources. UFZ is significantly contributing to the next DECOVALEX phase in model benchmarking.

Cross-Cutting Activities and Alliances. T8 has extensive cross-topic activities with T3, T5 and T6, specifically addressing geodynamics, natural hazards and anthropogenic impacts on the land and oceans as well as the development of simulation platforms coupling physical, chemical and biological processes. Our relevant research results will be integrated into the CTAs DE and ESM. The geothermal research in T8 is also part of the CARF Geoenergy, which includes contributions from GFZ and UFZ in RF E&E, and from KIT in RF Energy. The iCROSS project on the integrity of nuclear waste repository systems is a cooperation linking UFZ and GFZ (RF E&E) with KIT, FZJ and HZDR (NUSAFE in RF Energy), and will be part of the CARF Nuclear Repository Research. In addition, GFZ and HZG (RF E&E) have a proposed cooperation with KIT and HZDR (RF Energy) within CARF HI-CAM, addressing options for a net-zero emission scenario in urban areas. On a smaller scale, GFZ researchers collaborate with DESY partners in RF Matter (synchrotron-based experiments) and with HZDR (synthesis of materials for high-tech applications). Finally, our research on geothermal systems and induced seismicity in urban areas contributes to CARF Resilient Urban Spaces.

Transfer and contribution to SynCom. T8 is uniquely positioned for Technology and Knowledge Transfer to industry and government stakeholders as well as academic partners, nationally and worldwide. Each center has a Technology Transfer Office; these will be part of new network at the RF level (see Ch. 1.4.1 and 1.4.4) and will optimize collaborative approaches between the centers. Successful technology transfer has been demonstrated at our geothermal power plant in Lahendong and the carbon storage facility at Ketzin. Our teams also have extensive experience in technology transfer through partnerships with industry (explained above). Building on this relationship, one major objective will be to develop tools for the integration and analysis of the very large and varied Earth science data sets that are generated during commercial resource exploration and development, but have traditionally not been part of Earth System Research. This will be achieved partly through the CTAs Digital Earth and ESM. An further example is the proposed core-log seismic integration platform, which will significantly extend geoscience knowledge available from existing industry sample archives and repositories.

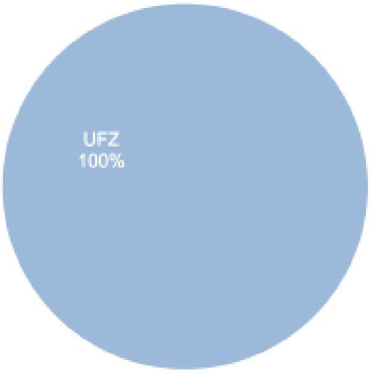
T8 will also develop geoscience-based information products on resource availability to support government and business in decision-making for investment and future actions related to the energy transition and raw materials supply. Through SynCom we will run workshops and engage in dialogue processes that deal with themes such as the urban geothermal systems, deep sea mining and/or the storage of energy in the subsurface and if required, we will produce fact-based position documents for stakeholders. We will actively use SynCom for outreach and education. For example, its predecessor, ESKP published a special issue on mineral deposits in the deep oceans in December 2018 and we envisage more theme focused products such as this one. Finally, we will work with colleagues in T3 to contribute to task forces focused on resource-related, induced seismicity issues if the need arises.

Executive Summary

- T8 is one of the few platforms worldwide that will combine research teams on energy and raw materials with an exclusive focus on deep georesources in both natural and engineered systems and their ancient analogs. We will focus our research on geothermal fluid circulation, mineral systems, the important role of geodynamic controls on resource formation and production, and advanced modeling of subsurface interactions. The Topic research will be uniquely positioned for Technology Transfer to industry and government stakeholders.
- Unlocking the Earth's deep and unconventional resources has the potential to dramatically increase global raw material security and supply, and help secure a reliable, economically efficient, and environmentally friendly energy mix for the energy transition. We will quantify scientific processes that are key to the successful subsurface storage of energy and waste materials and develop workflows for long-term monitoring of such underground facilities. This immediately and directly contributes to several Program research objectives on climate (2, 3 10), resources (8), and a safe and habitable environment (4, 5).
- T8 addresses natural resources as a fundamental limiting factor for human development. The critical advances in PoF IV will be the new 4D earth modeling of energy and mineral systems, which links near-surface observations to the deep subsurface at a range of scales, from geochemical tracers of fluid flow in fractures to regional geodynamic controls. The Topic will be linked to T3, T5 and T6 and connects RF E&E to RF Energy so that the future development of energy and raw materials intersects with research on local environmental impacts and long-term effects (e.g., climate change, extreme events).

Topic 9: One Healthy Planet – Developing an Exposome Approach to Integrate Human and Environmental Hazard Assessment

Spokespersons: Beate Escher and Rolf Altenburger, UFZ



The mission of Topic 9 is to work towards a healthy environment that is minimally compromised by chemical pollution and safeguards health and well-being of people. The quality of our lives has improved using services provided by chemicals but environmental pollution contributes to burden of disease and causes adverse environmental effects. We are exposed to a multitude of chemicals through multiple pathways from different sources. Topic 9 proposes new approaches to advance hazard assessment by accounting for the totality of chemicals in our bodies and the environment and by relating exposure to mixtures of chemicals through mechanistic networks to adverse outcomes. The acquired knowledge will support sustainable chemistry and improve environmental monitoring.

A) Scope and challenge of the Topic

Research subject: The exposome challenge. Organisms in their environment are exposed to a multitude of potentially harmful substances. 16% of all global premature human deaths are estimated to be attributable to pollution.[232] The exposome encompasses an individual's exposure to exogenous chemicals as well as endogenous compounds that are produced or altered in response to external stressors.[233] The eco-exposome defines the analog for all non-human organisms. Just to describe the exposome is already daunting due to the existence of millions of chemicals with tens of thousands estimated to be in current commercial use. We also need to understand the biological effects associated with the exposure. Linking the exposome approach to an understanding of the adverse outcome pathways[234] will have the potential to relate exposure causally to health outcomes and adverse ecological effects and hence provide mechanism-based tools for hazard prediction (Fig. 9.1)[235]

[232] Landrigan PJ, et al. 2018 The Lancet Commission on Pollution and Health. The Lancet. 391: 462–512.

[233] Wild CP. 2005. Complementing the genome with an "exposome": The outstanding challenge of environmental exposure measurement in molecular epidemiology. Cancer Epid Bio Prev. 14(8):1847–1850. Rappaport SM, Smith MT. 2010. Environment and disease risks. Science. 330(6003):460–461.

[234] Ankley GT, et al. 2010. Adverse outcome pathways: A conceptual framework to support ecotoxicology research and risk assessment. Environ Toxicol Chem. 29(3):730–741.

[235] *Escher BI, Hackermüller J, Polte T, Scholz S, Aigner A, Altenburger R, et al. 2017. From the exposome to mechanistic understanding

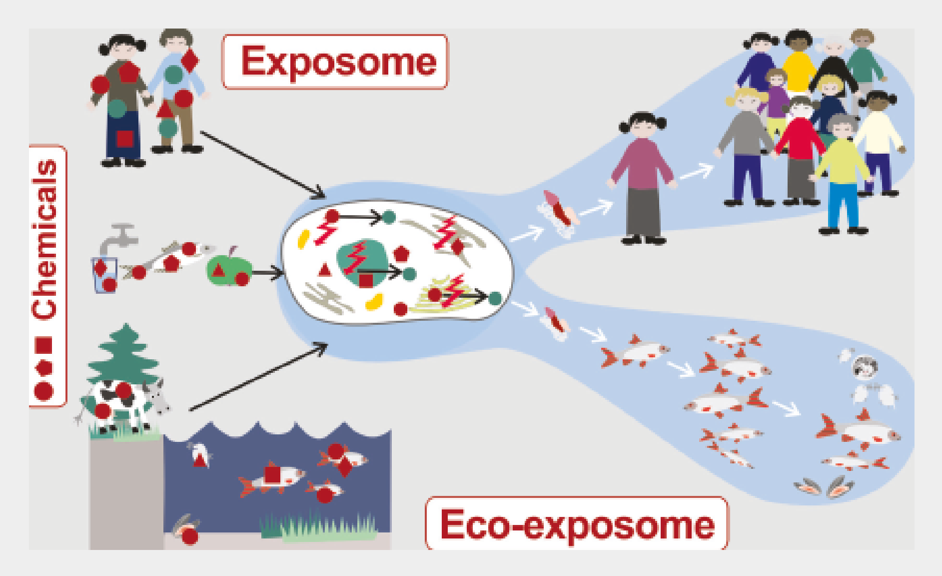


Fig. 9.1: The exposome challenge in relation to risk of chemicals and their adverse outcome for humans and the environment. Figure simplified from Escher et al.[235]

Topic 9 (T9) aims at understanding the fate and effects of chemicals from both an ecosystem and a human health perspective. It strives to aggregate different stressors for their joint impact. Understanding of the sources, fate and effect of mixtures of chemicals in the environment, including biota and humans, informs approaches for design of sustainable chemicals and their integrated risk assessment (Fig. 9.2). It enables better design of future monitoring and management strategies. This research provides tools for coping with the food-water-energy security nexus in collaboration with other Topics of the Program.

T9 seeks to innovate risk assessment by introducing novel concepts and methods to deal with mixtures and demonstrating their use in real-world landscape-scale case studies (Fig. 9.2). Synergies will result from integrating environmental chemistry with systems biology, ecology and epidemiology. This approach promises to contribute to a mechanistic understanding of disease and adverse ecological outcomes that supports the EU strategy for a non-toxic environment.[236]

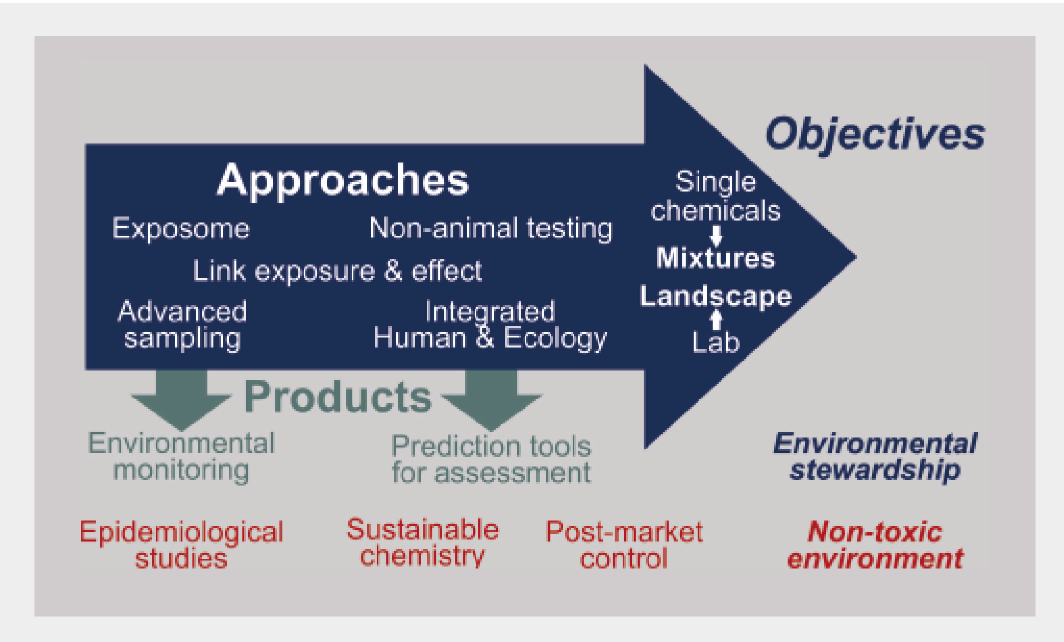


Fig. 9.2: Scope and approaches of T9.

of chemical-induced adverse effects. Environ Int. 99:97–106.

[236] The 7th Environment Action Programme adopted in 2013 by the European Parliament and the Council, mandated the European Commission to develop a "Union strategy for a non-toxic environment that is conducive to innovation and the development of sustainable substitutes including non-chemical solutions." The strategy is still pending and is expected to provide a long-term vision until 2050.

Explanation and justification of research. Modern societies rely on services provided by chemicals to secure food production and to serve as pharmaceuticals, industrial commodities, and as products for daily needs. At the same time, we understand that human health and ecosystem services may be severely impacted by the ever-growing use of chemicals and resulting environmental contamination. International development goals and the recent Global Environmental Outlook of UNEP,[237] therefore, call for sustainable production and consumption of chemicals and comprehensive health considerations. Research in T9 will develop hazard assessment tools for the environment and human health, provide monitoring tools and support mitigation strategies. The results of T9 will also contribute to the requested transformative agenda fostering sustainable chemistry,[238] enabling multifunctional agriculture and supporting healthy urban areas. Social science analyses will offer interaction with stakeholder-specific risk perspectives that may affect both management options and the regulation of chemicals.

Strategic guidelines (FoPoZ). The chemicals-related FoPoZ that ask for characterizing the (eco)exposome in conjunction with environmental monitoring will be central to T9 research. We cover the FoPoZ with the development and application of methods for non-invasive sampling and combined chemical and biological analysis of environmental samples. Evaluation of health and ecological effects will specifically address the mixtures' challenge. The opportunities of big data and digitalization will be explored with respect to multi-omics methods and their integration into hazard assessment. Mechanism-based prognostic hazard assessment should foster integration of environmental and human health perspectives. It also supports the design of sustainable chemicals. Site-specific risk assessment will improve environmental management and compare alternative regulatory options.

Function and contribution of the Topic within the Program. T9 will provide the expertise for identifying complex chemical exposure and combined effects in humans and the environment. T9 will look at ecosystems and the anthroposphere from a holistic perspective covering entities, e.g., the water cycle from pristine to polluted environments. This generic perspective will complement T4 on specifying the assessment of fate and risk of pollution in coastal land-sea-atmosphere systems. Collaboration with T5 will address the provision of environmental quality and societal monitoring approaches. With T6 we can address the question of host and microbiome related effects. Interaction with T7 regards indicators for bioeconomy-based processes. We support the EU strategy for a non-toxic environment by research into the life cycles of existing and new chemicals. T9 will provide a bridge between RF E&E and RF Health fostering the common mission of a healthy environment that supports human health worldwide.

Highlights. T9 tackles the mixture challenge. It will integrate human health and environmental risk assessment in the spirit of the exposome, considering the totality of exposure to complex and ever-changing mixtures. Predictive models for effect assessment will be based on understanding the mechanism of toxic action. We explore chemicals' inherent transformation capacity in relation to environmental (bio)degradation potential from the laboratory to the landscape scale, as well as the metabolic capacities of organisms, and the role of the microbiome to support benign-by-design chemicals. High-throughput techniques for screening (bio)analytics and alternative toxicity testing methods will be important cornerstones in future risk assessment.

B) Main research and structural objectives

Research Objectives.

- **Objective 1:** To develop the scientific foundation of an understanding of the (eco)exposome that integrates internal measures of the exposome in biota and humans (biomonitoring) with external proxies of the exposome.
- **Objective 2:** To develop methods and models for characterizing the exposome and linking it via internal changes at metabolic, immune and epigenetic levels to adverse outcomes.

[237] United Nations Environment Programme, Global Environment Outlook 6: Healthy Planet, Healthy People, March 2019, https://www.unenvironment.org/global-environment-outlook.
[238] ISC3 International Sustainable Chemistry Collaboration Center, see https://www.isc3.org/en/activities.html.

- **Objective 3:** To understand transformation of chemicals in the environment, by the (human) microbiome and by metabolism in humans and biota as a combination of principles of reactivity with system properties.
- **Objective 4:** To advance sampling and extraction techniques and (bio)analytical tools for a more comprehensive identification of anthropogenic chemical pollution (including anthropogenic particles) and for biomonitoring.

Structural Objectives.

- **Objective 5:** To work towards replacement of animal testing according to the 3R principles of reducing, refining and replacing animal testing by computational and in vitro methods.
- **Objective 6:** To become the European research leader in screening and non-target analytical, bioanalytical and ecological methods through fostering development of high-throughput research infrastructure combined with tailor-made data science applications.
- **Objective 7:** To develop open-access solutions to disseminate acquired risk assessment information, complementing large international efforts such as ChemSpider (Royal Society of Chemistry, UK) or the Chemical Dashboard (US EPA).

C) Structure of the Topic and motivation of Subtopics

Introduction of Subtopics. T9 tackles the exposome challenge in three Subtopics (Fig. 9.3). The fundamental scientific basis is laid in ST9.1 where we explore the idea of the exposome regarding its detectability and relevance for explaining compromised biological functioning. We will develop indicators of the exposome across different levels of biological complexity trying to substitute invasive measures with non-invasive proxies. We will elucidate the possibilities to link mixture exposure to adverse outcome, hypothesizing that key event detection simplifies mixture assessment. The human microbiome[239] will be studied as complementary biological determinant of chemical fate. In ST9.2 we develop tools to support design of sustainable chemicals and prospective risk assessment. One focus will be on chemicals' transformation capacity, where we will explore chemical-inherent information on reactivity and transformation pathways to address the metabolic capacities of organisms[240] and environmental (bio)degradation[241] up to the landscape level. The other focus is to improve the effect assessment by implementing alternative test methods building on the molecular mechanisms of toxicity. In ST9.3, we develop innovative approaches for environmental monitoring[242] and management. These address complex mixtures of chemicals as well as anthropogenic particles, their interaction under conditions of climate change and their large-scale impacts on human health and the ecosystems.[243]

Contributions of the Centers to the Topic. The main contributor to T9 is **UFZ** with collaborators from T4 and T5 for the landscape scale context and regarding analyses of societal impacts, and with T6 further links are planned on host-microbiome interactions and marine pollution. From T7 relevant processes and trends in bioeconomy and circular economy will be identified. RF Health (HGMU) will complement the wider human health perspective, with detailed knowledge on the link between environmental factors and allergy, inflammation, the microbiome and metabolic diseases.

[239] *Markle, et al. 2013. Sex Differences in the Gut Microbiome Drive Hormone-Dependent Regulation of Autoimmunity. Science. 339:1084–1088.

[240] *Oberbach A, et al. 2017. Metabolic in vivo labeling highlights differences of metabolically active microbes from mucosal gastrointestinal microbiome between high-fat and normal chow diet. J Proteome Res. 16:1593–1604.

[241] *Harms H, et al. 2011. Untapped potential: exploiting fungi in bioremediation of hazardous chemicals. Nature Rev Microbio. 9:177–192.

[242] *Altenburger R, et al. 2015. Future water quality monitoring – Adapting tools to deal with mixtures of pollutants in water resource management. Sci Total Environ. 512-513:540-551.

[243] *Brack W, et al. 2015. The SOLUTIONS project: Challenges and responses for present and future emerging pollutants in land and water resources management. Sci Total Environ. 503-504:22–31.

TOPIC 9 | One Healthy Planet – Developing an Exposome Approach to integrate Human and Environmental Assessment

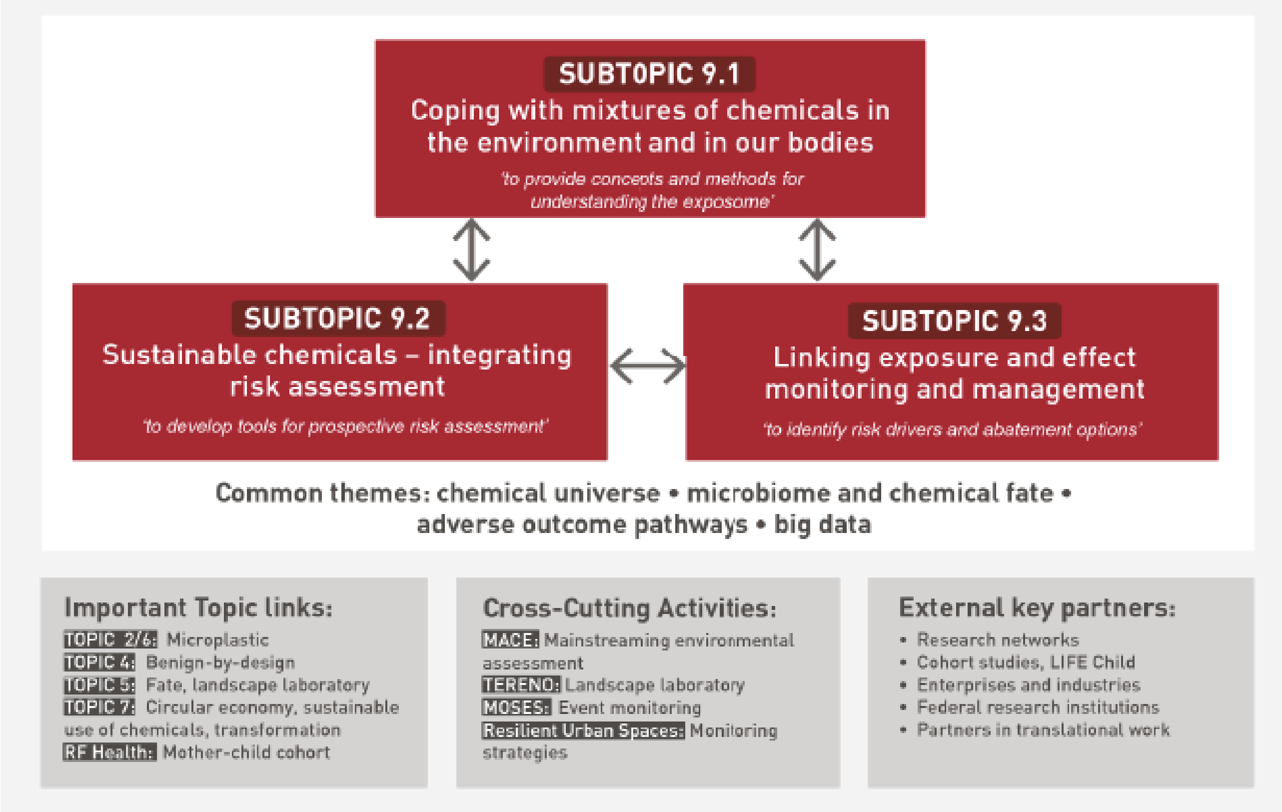


Fig. 9.3: Subtopics of T9, their main aims and how they link to other Topics, CCAs and external partners.

D) Subtopics

Subtopic 9.1 Coping with mixtures of chemicals in the environment and in our bodies

Martin von Bergen, UFZ

Scope and challenges. Organisms have to cope with complex mixtures of chemicals in their environment and take up mixtures over multiple pathways from their food and environment. This Subtopic provides the methodological advancement for understanding this exposome. In PoF III research the exposome was conceptualized.[244] Now the comprehensive understanding of exposure is envisaged to move into a hazard context. It requires expanding quantification of selected mixtures of known components to a holistic evaluation, understanding and aggregated assessment of associated health and environmental risks.

Main objectives. The detection of multiple chemicals in diverse biological matrices will progress with novel analytical instrumentation and methods such as non-target screening and multi-component monitoring (Fig. 9.4). In order to associate biomonitoring findings with environmental exposure we plan to develop non-invasive methods. This provides more easily accessible proxies, e.g., by sampling chemicals with silicone wrist bands.

Mixture risk assessment has to account for changing exposure, potentially life-long and over multiple pathways. Risk from complex exposure can be addressed through detailed knowledge about mechanisms of joint action and cause-effect relationships. The Adverse Outcome Pathway (AOP) concept provides a starting point

[244] *Escher BI, Hackermüller J, Polte T, Scholz S, Aigner A, Altenburger R, et al. 2017. From the exposome to mechanistic understanding of chemical-induced adverse effects. Environ Int. 99:97–106.

that can be extended to network thinking[245] to develop hypotheses that include mixtures in cause-effect relationships (Fig. 9.4). Within the next years, we aim to discover (molecular and physiological) key events in AOP networks in order to extrapolate from component effects to chronic joint effects of chemical mixtures.

To understand causes of disease, we will evaluate environment-health interactions with a focus on early life exposures (Fig. 9.4) including the prenatal phase[246] using existing and prospective cohort studies. Measures of the external exposure, social aspects and lifestyle factors including nutrition and urban context shall be connected with the human exposome. This includes internalized chemicals and their transformation products, immune parameters, microbiome and 'omics'. A special emphasis will be given to unraveling the relationship between the exposome of children and diseases, focusing on disorders of immunity, growth and development.

The microbiome can be a stressor/benefactor but can also be a modifying factor of the fate of chemicals. The organismic microbiome has been found to be a relevant factor for developing and maintaining health for higher organisms.[247] The exposure to environmental stressors interferes with the ecological equilibrium and may cause microbial malfunctioning, called dysbiosis. We will explore the physicochemical principles of microbiota-driven transformation and seek to understand the mode of action by which altered interactions within the microbiota may lead to dysbiosis.

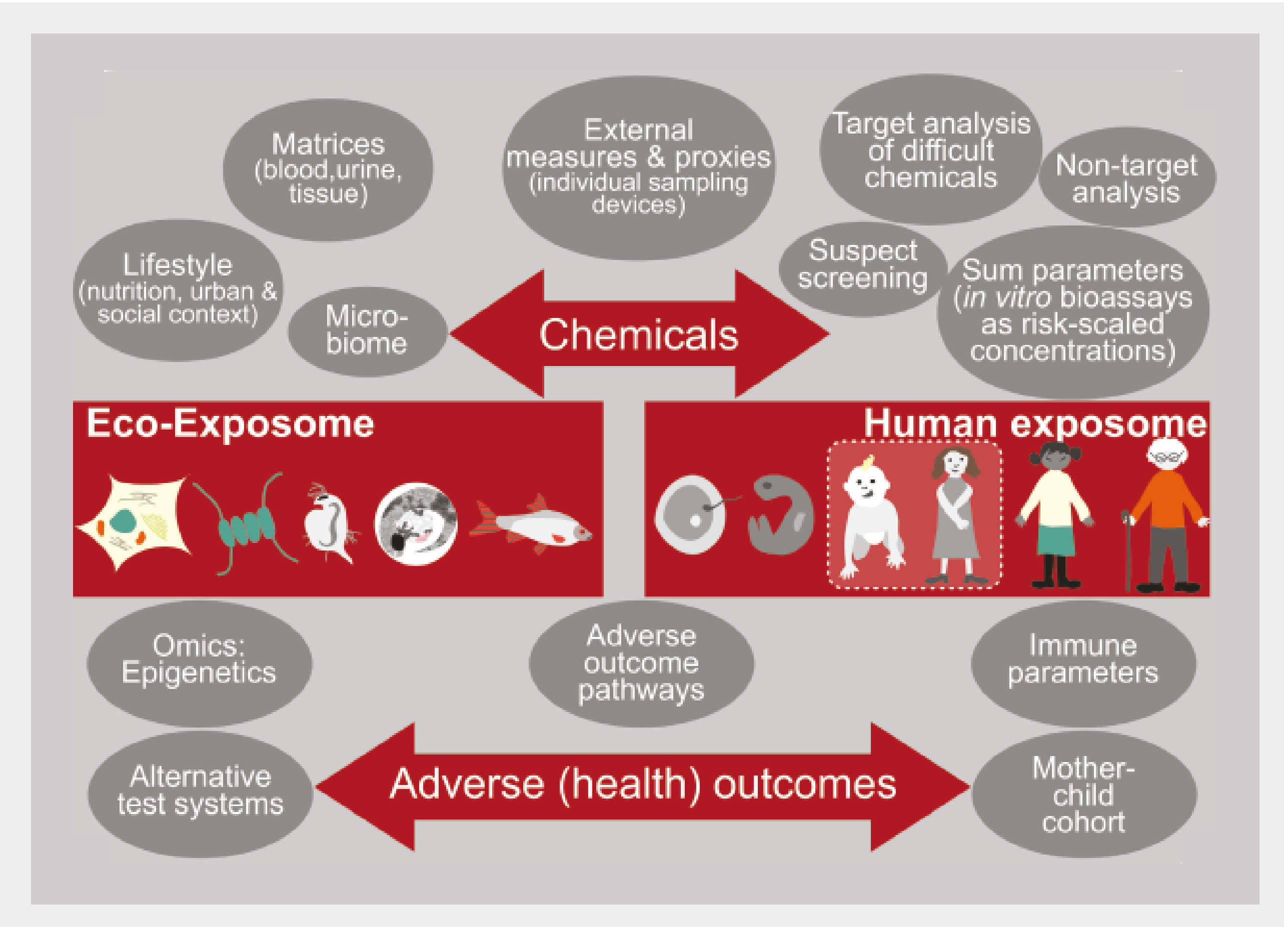


Fig. 9.4: Approach to account for mixtures in Subtopic 9.1.

245 *Schüttler A, et al. 2019. Map and model–moving from observation to prediction in toxicogenomics. GigaScience 8:1–22.

246 *Trump S, et al. 2016. Prenatal maternal stress and wheeze in children: novel insights into epigenetic regulation. Sci Rep 6: 28616. *Bauer T et al. 2016. Environment-induced epigenetic reprogramming in genomic regulatory elements in smoking mothers and their children. Molecular Systems Biology. 12(3):861.

247 Heijtz RD, et al. 2011. Normal gut microbiota modulates brain development and behaviour. Proc Nat Acad Sci. 108:3047–3052.

Work program.

Exposome measures. We will establish approaches for quantification of the eco-exposome and the human exposome. We use targeted methods for chemicals of identified risk and non-targeted analytical methods, which will allow characterization of chemical exposure patterns. To identify suspect chemicals, a data-driven smart grouping of compounds will be pursued. The integration of curated chemical exposure and effect data in a digital 'Chemical Universe',[248] will additionally boost the identification of patterns. Here we will use statistical methods, semantic web technologies like Linked Open Data (LOD), and utilize artificial intelligence.

We will develop and assess sampling methods, which could serve as non-invasive proxies for the assessment of aggregate exposure, e.g., by expanding the chemometer approach to human biomonitoring.[249] This will include silicone wristbands and other types of passive sampling devices as well as non-invasive human samples such as saliva. Non-invasive approaches will be particularly relevant for future mother-child cohort studies. We will also explore the relationship with other proxies for human exposure such as house dust, drinking water and diet.

AOP networks. Major innovation is expected from looking into combined effects from mixture exposure. Chemicals in mixtures can be grouped by how they act together. Adverse Outcome Pathways (AOP) and networks will play a major role to connect the actual exposure with joint adverse effects.[250] The development of AOP networks will build on i) the identification of archetypical mixtures of environmental and human health relevance and their spatio-temporal dynamics, ii) the system-based effect detection at various levels of biological organization, and iii) the transformation of biological standard model systems to establish knowledge and models on the dynamics of effect-effect relationships.

A specific focus for health-outcomes will be on childhood diseases, many of which emerge from a dysregulation at the immune system level. Additionally, multi-layer 'omics' (i.e., epi/genomics, proteomics, transcriptomics, metabolomics, flux 'omics') and single cell analyses will be used to perform case studies for AOPs and devise tools for dealing with data-sparse settings. To validate epidemiological findings from retrospective and prospective cohort studies and to address the underlying causal mechanisms, we will employ disease-specific in vivo and in vitro models.

Microbiome. The relationship between exposure and adverse health outcomes will further be scrutinized for the modifying role of the microbiome (gut, skin, and nose). We will use models covering different degrees of complexity: from simplified consortia in bioreactors to complex communities in animal models up to analyses in children's cohorts to explore the role of the microbiome as exposure-measure and modifier of chemical exposure. In vivo models using gnotobiotic (i.e., sterile) animal models will be established to demonstrate causal links between chemical exposure, microbiome and disease outcome. By integrating multi-omics analyses, we aim at mechanistic understanding of microbial ecology and interactions in response to environmental stressors and their impact on potential microbial malfunctioning, called dysbiosis. We will compare the environmental microbiome and the human microbiome and correlate their time and spatial patterns with detected dysbiosis and childhood diseases. These insights will be translated into dysbiosis alerts for an improved risk assessment.

Deliverables (D) and Milestones (M)

- **D9.1 (2027)**: Digital patterns of environmental exposure and health. **M9.1-1 (2023)**: Strategies for assessing (eco-)exposome typologies using non-target analytics and bioanalytical effect detection. **M9.1-2 (2024)**: Documentation of procedures for assessing the exposome in cohort studies. **M9.1-3 (2025)**: Immune parameters and 'omics' in cohorts and links of chemical exposure proxies with health-related endpoints.

[248] Fink T, Reymond JL. 2007. Virtual exploration of the chemical universe up to 11 atoms of C, N, O, F: assembly of 26.4 million structures (110.9 million stereoisomers) and analysis for new ring systems, stereochemistry, physico-chemical properties, compound classes and drug discovery. Chem Inf Model. 47:342–353.

[249] *Jahnke A, et al. 2014. Silicone passive equilibrium samplers as 'chemometers' in eels and sediments of a Swedish lake. Environmental Science: Processes & Impacts. 16(3):464–472.

[250] *Escher BI, Hackermüller J, Polte T, Scholz S, Aigner A, Altenburger R, et al. 2017. From the exposome to mechanistic understanding of chemical-induced adverse effects. Environ Int. 99:97–106.

- **D9.2 (2026):** Computational tools to unravel AOPs and potential adverse effects from high-throughput bioassay and multi-omics data. **M9.2-1 (2024):** Linking effect signatures to AOPs.
- **D9.3 (2027):** Identification of chemicals causing dysbiosis and associated mechanisms. **M9.3-1 (2023):** Standardized test systems for testing microbiota affecting chemicals to derive dysbiosis alerts. **M9.3-2 (2025):** Identification of dysbiosis alerts.

Risks and Opportunities. Risks are failing to develop a new larger-scale mother-child cohort or failing to develop adequate novel methods for sampling and/or mixture analysis, potential fragmentation of resources and focus with respect to immune parameters. Contingency and opportunities include adoption of newly established methods from others, e.g., European large-scale cohorts. On the microbiome theme, we might have insufficient resources for gnotobiotic animals needed for proving a microbiota-dependent effect, which can be overcome by expanding existing collaborations. If we can join efforts with the federal research institutions BfR and UBA for risk assessment we can be leading the forefront of translational research.

Subtopic 9.2 Sustainable chemicals – integrating risk assessment

Lukas Wick, UFZ

Scope and challenges. The ability to withstand biotic and abiotic transformation makes chemicals long-lasting and it has been argued that considering persistence should suffice for precautionary measures (P-sufficient approach[251]). A chemical would be benign by design if it is ultimately degraded fast and without the production of harmful or persistent intermediate transformation products.

Effect assessment, needed to relate chemical occurrence to biological potencies for the estimation of risk, has been struggling with the controversial reliance on animal testing. Alternative test methods, including computational approaches and in vitro test systems, are only slowly moving into the regulatory space.[252] A paradigm shift from observational hazard (animal) testing to a hypothesis- and mechanism-driven approach requires extracting maximum information from in vivo tests and developing quantitative in vitro to in vivo extrapolation methods (QIVIVE).

Main objectives. We aim at understanding chemicals' fate and persistence from an ecosystem perspective. Our goal is to identify key factors controlling the long-term functional performance of ecosystems with regard to (bio)degradation of chemicals and the capacity of microbial ecosystems to adapt to environmental changes at different scales. To apply this knowledge in chemical risk assessment, we develop tools to understand and predict the persistence of chemicals based on their molecular structure and environmental conditions.

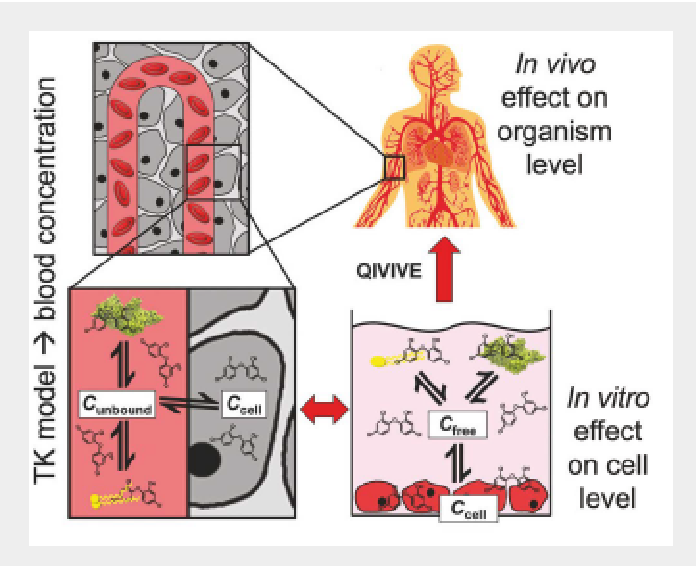


Fig. 9.5: Approach for in vitro to in vivo extrapolation (QIVIVE) in ST9.2. (Figure reprinted from Fischer et al. 2017[253]).

[251] Cousins IT, et al. 2019. Why is High Persistence Alone a Major Cause of Concern? Environmental sciences: Processes & Impacts. 21:781–792.

[252] *Sobanska M, et al. 2018. Applicability of the fish embryo acute toxicity (FET) test (OECD 236) in the regulatory context of Registration, Evaluation, Authorisation, and Restriction of chemicals (REACH). Environ Toxicol Chem. 37(3):657–670.

For the effect component of risk assessment our focus will be on a weight-of-evidence approach using alternative test methods according to the 3R principles. A smart combination of computational tools with in vitro models (Fig. 9.5) is geared towards utilization in chemical design to avoid future 'regrettable substitutions'.

To implement an integrated testing strategy[263,264] and alternative test methods in risk assessment and monitoring several knowledge gaps need to be filled, including i) quantitative dosimetry and toxicokinetics in in vitro test systems,[265] ii) (quantitative) in vitro to in vivo extrapolation (QIVIVE)[266,267] (Fig. 9.5) that goes beyond correlation analysis, and iii) comprehensive toxicodynamics analysis expanding in vitro approaches.

Work program.

Persistence. For the experimental high-throughput approaches to understand the transformation of given chemicals under various conditions, we will explore different types of conditions, for example, light-induced, anoxic or high/low pH conditions. We plan to develop high-throughput testing on model chemicals representing structural or reactive classes of chemicals under sets of reaction conditions. Studies will include the identification of transformation products. We will use the chemicals' inherent properties and link them to microbial degradation and metabolic transformation processes in organisms to derive mechanistic models of persistence.

Hazard. Our focus is on alternative test methods with the capacity to investigate high numbers of chemicals in order to develop predictive computational models that support the design of sustainable chemicals. We differentiate between the toxicokinetics (TK: absorption, distribution, metabolism and elimination) and the toxicodynamics (TD: all steps of an AOP) (Fig. 9.6). For TK, we address membrane permeability, biotransformation and active transport of ionizable organic chemicals for improved prediction of toxicokinetics.

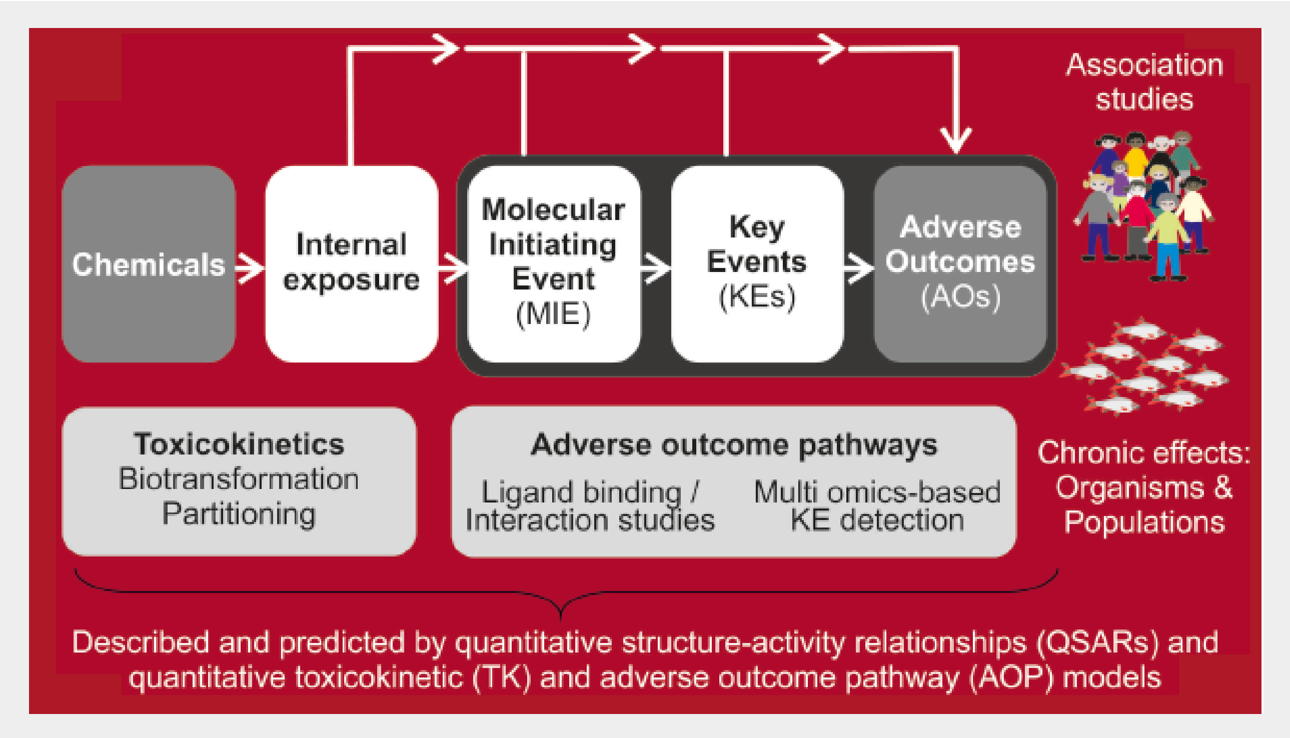


Fig. 9.6: Approach for integrated hazard assessment in Subtopic 9.2.

[253] Blaauboer BJ. 2015. The long and winding road of progress in the use of *in vitro* data for risk assessment purposes: From "carnation test" to integrated testing strategies. Toxicology. 332:4–7.

[254] *Rovida C, et al. 2015. Integrated testing strategy for safety assessment. ALTEX 32:25–40.

[255] *Fischer F, et al. 2017. Modelling exposure in the Tox21 in vitro bioassays. Chem Res Toxicol. 30:1197–1208.

[256] Wetmore BA. 2015. Quantitative *in vitro*-to-*in vivo* extrapolation in a high-throughput environment. Toxicology. 332:94–101.

[257] *Larisch W, et al. 2017. A toxicokinetic model for fish including multiphase sorption features. Environ Toxicol Chem. 36:1538–1546.

The goal of the TD component is to integrate experimental and model approaches. We will use experimental and computational analyses (QSARs, ligand-receptor interactions including molecular docking studies) as well as characterization of molecular initiating events and key events of AOPs using in vitro assays. Data from all steps will be integrated to predict adverse outcomes and to develop quantitative AOPs. This will support future predictive hazard assessment.

Deliverables (D) and Milestones (M)

- **D9.4 (2027):** Predictive models on persistence involving machine learning supported by mechanistic approaches. **M9.4-1 (2024):** Comparative biotransformation analyses.
- **D9.5 (2025):** Quantitative in vitro to in vivo extrapolation models for human and aquatic organisms. **M9.5-1 (2023):** Implementation of alternative test methods and models (PBTK models, QSAR, molecular docking).

Risks and Opportunities. A comprehensive approach might not lead to short-term visibility or progress. Further risks are changes in the regulatory landscape which might require adaptations in the research strategy or focus. Opportunities are to transform the observational testing paradigm in Europe towards a mechanistic toxicology approach inspired by the US' National Toxicology Program.[258] The development of predictive models for the transformation of chemicals promises new horizons in research towards sustainable chemistry.

Subtopic 9.3 Linking exposure and effect monitoring and management

Annika Jahnke, UFZ

Scope and challenges. Water quality management relies on monitoring. Information gaps in substance domains, space and time limit the effective management of chemicals. Moreover, climate change may become a game-changer for monitoring and management. The Subtopic will provide means for unbiased monitoring, to identify risk drivers of adverse effects and for weighing abatement options for complex mixtures of contaminants (Fig. 9.7). It will address the interaction of chemical exposure with non-chemical stressors.[259] After

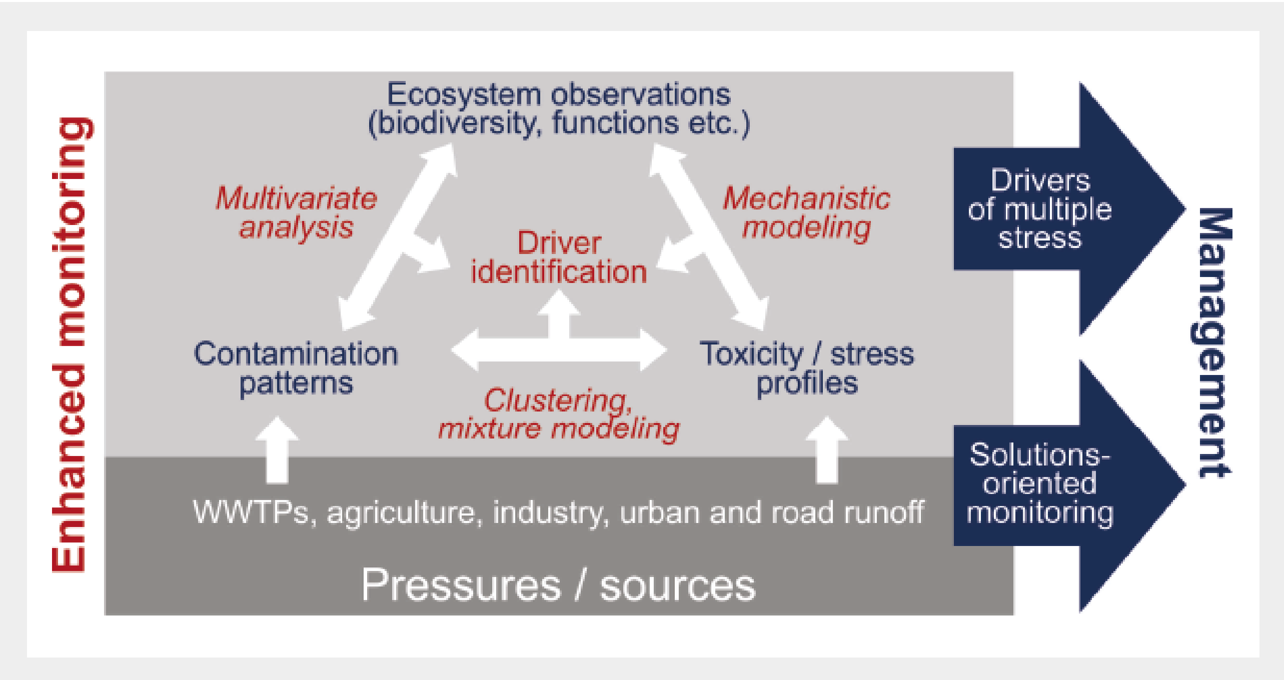


Fig. 9.7: Approach for enhanced monitoring in Subtopic 9.3.

[258] National Research Council. 2007. Toxicity testing in the 21st century: A vision and a strategy. Washington DC.
[259] *Liess M, et al. 2016. Predicting the synergy of multiple stress effects. Scientific Reports. 6:32965.

release into the environment chemicals as well as anthropogenic particles on the macro-, micro and nanoscale stemming, e.g., from plastic litter, are subject to fate and transport processes[260] and possibly cause biological effects[261] or act as vectors of chemicals.[262]

Advances in analytical and bioanalytical techniques provide increasingly data-rich and complex datasets. Data analysis approaches, like machine learning or LOD integration have proven highly successful in life sciences but comparable approaches for big data evaluation in the environmental sciences are lagging behind and will be a focus of ST9.3.

Main objectives. The goal is to foster solution-oriented chemicals management with a focus on identification of mixture risk drivers. Thus environmental surveillance will be expanded from monitoring of known chemicals in water to a stewardship view on ecosystems that establishes a wider look at chemical contamination in conjunction with non-chemical stressors (Fig. 9.7). This Subtopic will build on the achievements of ST9.1 and ST9.2, applying them to real-world landscape laboratories. The new monitoring strategy will be tailored for large sample numbers, mixture detection and multiple toxicological endpoints, to support the EU policy for a non-toxic environment (Fig. 9.7).[263]

The proposed research aims to establish a coherent monitoring framework for chemicals i) by advancing monitoring tools in terms of throughput capacity and diagnostic value, ii) by combining them into modules, which allow for comprehensive assessment of mixtures and their effects and iii) by including non-chemical stressors such as climate-driven changes including heat extremes as integral parts of monitoring. We will focus on the compartments surface water, sediment and aquatic biota and their interfaces.

Work program.

Monitoring toolbox. We will establish a monitoring toolbox for large-scale assessment of complex contamination and its natural attenuation. This includes an unbiased transfer of mixtures of chemicals from diverse environmental matrices into the laboratory. Also, expanding analytical methods will increase sensitivity, throughput and coverage of compounds. Non-target screening and multi-element compound-specific stable isotope analysis will be integrated to unravel the main sources and in situ transformation of chemicals. Bioanalytical testing will be expanded towards improved coverage of biological/toxicological endpoints.

Multiple stress. Adverse effects of chemicals in ecosystems are often enhanced by additional stressors. We will therefore develop techniques to detect such stressors and boundary conditions in the field. Stressor combinations will be studied at landscape scales with a diagnostic perspective: Existing examples are the Small Stream Event Monitoring[264] and the Joint Danube Survey.[265] Using such studies we will pursue the systematic integration of non-chemical stressors in testing and modeling strategies for the effect assessment of chemical mixtures.[266] Prioritization of abatement options for emissions of concern will be performed using approaches for regional toxic footprints calculation.

Particles. Anthropogenic particles may interact with dissolved constituents by various processes, e.g., by dissolution, sorption or leaching of dissolved chemicals. These may modulate the environmental relevance of anthropogenic particulate matter as well as associated chemicals. Our approaches to assess their environmental relevance comprise i) to characterize emissions of anthropogenic particles including plastic litter and pigments into terrestrial and freshwater environments (links to T4, T5, and T6), ii) to determine their transport pathways and sinks such as freshwater sediments or the marine environment, iii) to unravel environmentally relevant fate processes including solute-particle interactions and possible adverse effects on living biota (Fig. 9.8).

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260 *Wagner S, Reemtsma, T. 2019. Things we know and we don't know about nanoplastic in the environment. Nature Nanotechnology. 14:300–303.

261 *Jahnke A, et al. 2017. Reducing uncertainty and confronting ignorance about the possible impacts of weathering plastic in the marine environment. Environmental Science & Technology Letters. 4:85–90.

262 Koelmans AA, et al. 2016. Microplastic as a vector for chemicals in the aquatic environment: Critical review and model-supported reinterpretation of empirical studies. Environ Sci Technol. 50(7):3315–3326.

263 *Brack W, et al. 2017. Towards the review of the European Union Water Framework Directive: Recommendations for more efficient assessment and management of chemical contamination in European surface water resources. Sci Total Environ. 576 :720–737.

264 See https://www.ufz.de/kgm/index.php?en=44480 – Demonstration project on event-based monitoring of small rivers.

265 See http://www.danubesurvey.org/jds4/ – Investigative surface water monitoring project.

266 *Altenburger R, et al. 2015. Future water quality monitoring – Adapting tools to deal with mixtures of pollutants in water resource management. Sci Total Environ. 512–513:540–551.

Guidance. The individual approaches will be combined into larger modules. This synthesis will take place on a technological level (e.g., integration of sensors for in situ measurements of pH and redox potential), on a conceptual level (e.g., combining stable isotope analysis and suspect screening for transformation products) and also on the level of exposure modeling or hydrology-driven monitoring. These modules will be collated into a tiered monitoring strategy and tested in case studies for applicability for different management purposes.

Deliverables and Milestones

- **D9.6 (2027):** Monitoring combined with the analysis of adverse effects of chemicals and particles in humans and aquatic organisms. **M9.6-1 (2023):** Strategy to integrate multiple stress concepts into monitoring. **M9.6-2 (2026):** Map of chemical and ecotoxicological footprints of major pollution in selected river basins.
- **D9.7 (2025):** Quantitative assessment of the environmental relevance of anthropogenic particles in the environment. **M9.7-1 (2023):** Experimental tools for characterizing diverse types of particles and protocols for monitoring established.
- **D9.8 (2027):** Guidance document on environmental monitoring in support of the EU strategy for a non-toxic environment.

Risks and Opportunities. Risks include the failure of methods to reach the necessary performance for the intended task or a game-changing public perception on priorities, e.g., regarding climate change consequences. These and the threat of governance schemes delaying adoption of research innovations can be reduced by collaborating with social science research and by including stakeholders (regulation, chemical industry, bioeconomy) early in the development process. Cooperation within large-scale monitoring projects may provide opportunities for unforeseen applications and technical spin-offs.

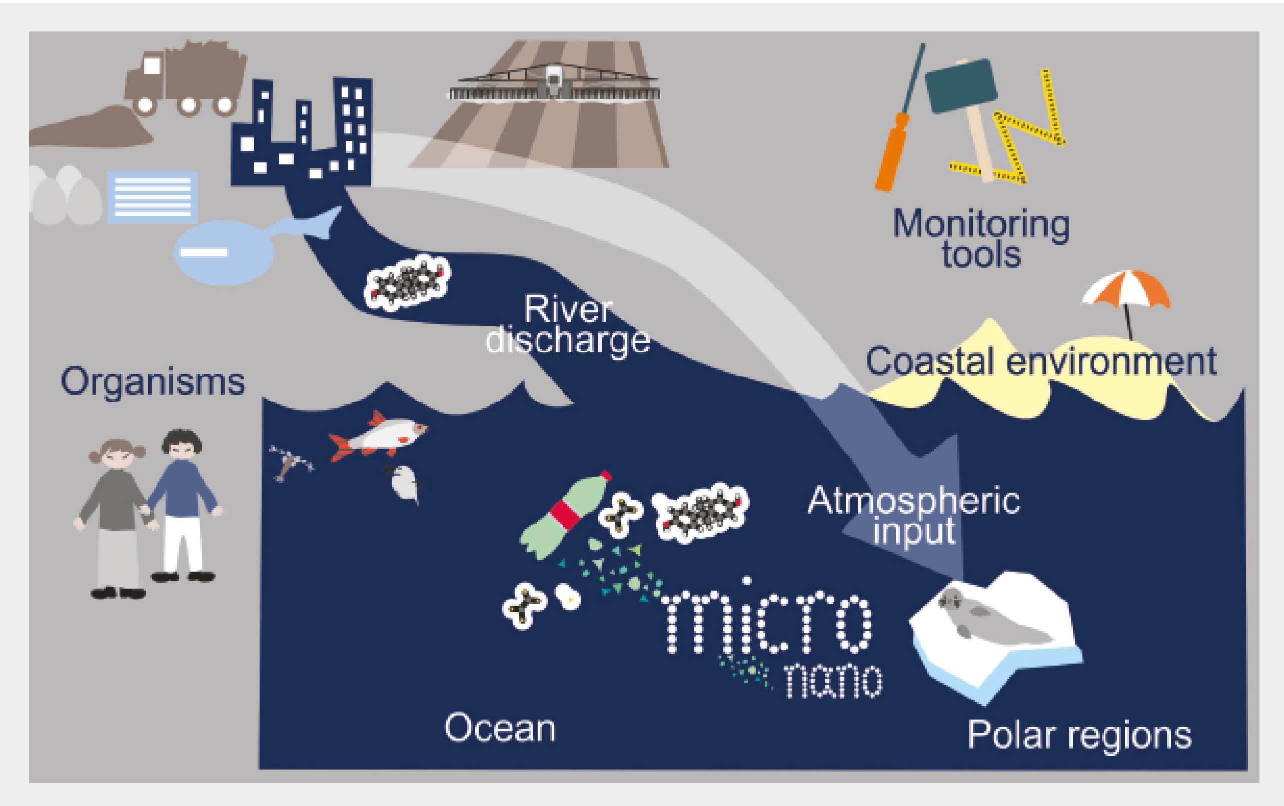

Fig. 9.8: Assessment of fate and effect of (plastic) particles and associated chemicals.

E) Previous achievements of the contributing centers and infrastructures

Expertise and preliminary work. In PoF III, we have achieved initial connections between prognostic and site-specific chemical hazard assessment work.[267,268] Further, we operationalized the exposome concept[269] and provided novel views on complex exposure,[270] fate[271] and effect[272] assessment. We achieved breakthroughs in toxicokinetic modeling through a combined experimental/modeling approach that provided access to difficult substances such as ionizable chemicals[273,274] and adapted toxicological model systems to describe AOPs for chemicals.[275,276] We have gained mechanistic insights into chemical-induced generation-bridging epigenetic modifications that connect maternal exposure to phthalates and other ubiquitous pollutants with adverse health outcomes like asthma.[277] Moreover, we established first experimental systems to elucidate the role of the endogenous microbiome for the fate and effect of chemicals[278,279] and have identified ways to explore the environmental behavior of plastic[280,281] and to assess multiple stress.[282]

Infrastructures. While analytical and in vitro testing platforms are well established at UFZ (MetaPro, ProVIS, CITEpro)[283] we need to expand our capacities for prospective mother-child cohort studies and high-throughput testing. Further, we will liaise with larger-scale observation infrastructures such as TERENO and MOSES to establish a landscape laboratory to study best management practices. From the collaboration with RF Health we can profit from the platform for advanced imaging technologies.

Uniqueness. During the PoF III period the research into chemicals' fate and effect has established well-recognized collaboration in interdisciplinary teams from chemical, biological, toxicological, ecological and health sciences. Coordination and leadership in various European large-scale research projects (e.g., SOLUTIONS, OSIRIS) substantiate a leading research role. The combination of conceptual approaches (exposome, AOP, effect-oriented monitoring) with analytical and bioanalytical infrastructures and expertise are unprecedented in Europe. It is visible in European networks for identifying substances of emerging concern such as the NORMAN network of reference laboratories, the European Topic Center on water or the human biomonitoring

[267] *Brack W, et al. 2015. The SOLUTIONS project: Challenges and responses for present and future emerging pollutants in land and water resources management. Sci Total Environ. 503-504:22–31.

[268] *Lombardo A, et al. 2014. Optimizing the aquatic toxicity assessment under REACH through an integrated testing strategy (ITS). Environ Res. 135:156–164.

[269] *Escher BI, Hackermüller J, Polte T, Scholz S, Aigner A, Altenburger R, et al. 2017. From the exposome to mechanistic understanding of chemical-induced adverse effects. Environ Int. 99:97–106.

[270] *Jahnke A, et al. 2014. Silicone passive equilibrium samplers as 'chemometers' in eels and sediments of a Swedish lake. Environmental Science: Processes & Impacts. 16(3):464–472.

[271] *Harms H, et al. 2011. Untapped potential: exploiting fungi in bioremediation of hazardous chemicals. Nature Rev Microbio. 9:177–192.

[272] *Lombardo A, et al. 2014. Optimizing the aquatic toxicity assessment under REACH through an integrated testing strategy (ITS). Environ Res. 135:156–164.

[273] *Fischer F, et al. 2017. Modelling exposure in the Tox21 in vitro bioassays. Chem Res Toxicol. 30:1197–1208.

[274] *Larisch W, et al. 2017. A toxicokinetic model for fish including multiphase sorption features. Environ Toxicol Chem. 36:1538–1546.

[275] *Schüttler A, et al. 2019. Map and model—moving from observation to prediction in toxicogenomics. GigaScience. 8:1–22.

[276] *Sobanska M, et al. 2018. Applicability of the fish embryo acute toxicity (FET) test (OECD 236) in the regulatory context of Registration, Evaluation, Authorisation, and Restriction of chemicals (REACH). Environ Toxicol Chem. 37(3):657–670.

[277] *Trump S, et al. 2016. Prenatal maternal stress and wheeze in children: novel insights into epigenetic regulation. Sci Rep 6: 28616. *Bauer T et al. 2016. Environment-induced epigenetic reprogramming in genomic regulatory elements in smoking mothers and their children. Molecular Systems Biology. 12(3):861.

[278] *Markle, et al. 2013. Sex Differences in the Gut Microbiome Drive Hormone-Dependent Regulation of Autoimmunity. Science. 339:1084–1088.

[279] *Oberbach A, et al. 2017. Metabolic in vivo labeling highlights differences of metabolically active microbes from mucosal gastrointestinal microbiome between high-fat and normal chow diet. J Proteome Res 16:1593–1604.

[280] *Wagner S, Reemtsma T. 2019. Things we know and we don't know about nanoplastic in the environment, Nature Nanotechnology. 14:300–303.

[281] *Jahnke A, et al. 2017. Reducing uncertainty and confronting ignorance about the possible impacts of weathering plastic in the marine environment. Environmental Science & Technology Letters. 4:85–90.

[282] *Liess M, et al. 2016. Predicting the synergy of multiple stress effects. Scientific Reports 6: 32965.

[283] MetaPro: Metabolomic Profiler, central bioinformatics and 'omics' platform at UFZ; ProVIS: Center for visualization of biochemical processes on cellular level, UFZ platform for chemical microscopy and mass spectrometry; CITEPro: Chemicals In The Environment-Profiler, (bio)analytical platform for a high-throughput screening of chemicals and environmental samples.

initiative HBM4EU. Moreover, dedicated science/policy interface activities resulted, e.g., in well-recognized recommendations for water quality monitoring in European rivers[284] and paved the way for demonstration projects such as on nationwide monitoring of small streams.[285] The team participates in policy advisory committees, private-public partnerships to prioritize compounds, think tanks to avoid regrettable substitution, and techniques for process quality control, e.g., in water abstraction or waste(water) treatment. In establishing a collaborative Center for Children's Environment Health we prepare for the further integration of human and environmental perspectives.

F) Collaboration and transfer

Partners. AWI, GEOMAR and HZG will participate as collaborators. HMGU will be the essential partner to streamline efforts across the RF E&E and the RF Health towards a 'One Health' perspective. Major strategic partners beyond Helmholtz are listed in Table 9.1. We build on established research and training partnerships at the national (Universities of Leipzig, Aachen and Tübingen), European and international level. We cooperate with the University of Leipzig, the University clinic and several regional research centers to establish a Center for Children's Environment Health, and bundle efforts for a next stage of a mother-child cohort. We continue to extend collaborations with larger cohorts with expertise in pediatrics and beyond to increase scope and test transferability of approaches. As T9 mainly deals with public goods, major strategic partnerships will be continued with federal institutions that have regulatory mandates (Table 9.1). Concerning the assessment of chemical persistence, interaction will be sought with the enviPATH platform.[286] The large initiatives Tox21 of the US NIEHS's National Toxicology Program Division and ToxCAST of the US EPA have been leading the way for the adoption of high-throughput screening for in vitro information for hazard assessment.[287] We seek to further deepen our existing collaborations with the US protagonists in this area[288,289] as well as expand our European networks.

Positioning of the Topic in international research. Scientists in T9 have a strong record in shaping, coordinating and participating in collaborative projects along the whole research value chain. Continued coordination of large EU-funded projects such as SOLUTIONS or OSIRIS demonstrates leadership roles. Obtaining prestigious international grants (e.g., ERC 'Chemometer' project) shows the scientific potential. We promote our concepts through international collaborations, e.g., with universities in China, Australia, Kenya, and Brazil. Our monitoring strategies have attracted funds for organizing international, coordinated research actions, such as for the Joint Danube Survey.

Cross-Cutting Activities and Alliances. Strong connections to T5 and T7 exist regarding the sustainable use and fate of chemicals in urban and agricultural environments. While T9 provides novel, generic approaches to address complex exposure comprehensively, T4 and T5 provide the context knowledge for defined landscapes. Joint development of specific management options and governance strategies promises novel routes for sustainable chemical services. T6 addresses the large-scale anthropogenic threats for the marine environment and T9 can support this effort on the chemicals' risk component. T4 supports efforts in T9 towards benign-by-design chemicals, while T9 contributes to understanding of inherent degradability. Landscape laboratories will be run across Topics. The T9 research into the immune system and the microbiome has a strong connection to the Topic

[284] *Brack W, et al. 2017. Towards the review of the European Union Water Framework Directive: Recommendations for more efficient assessment and management of chemical contamination in European surface water resources. Sci Total Environ. 576:720–737.

[285] See https://www.ufz.de/kgm/index.php?en=44480 – Demonstration project on event-based monitoring of small rivers.

[286] Latino DARS, et al. 2017. Eawag-Soil in enviPath: a new resource for exploring regulatory pesticide soil biodegradation pathways and half-life data. Environmental Science: Processes & Impacts 19(3):449–464.

[287] Tice RR, et al. 2013. Improving the human hazard characterization of chemicals: A tox21 update. Environ Health Perspect. 121(7):756–765.

[288] Wild CP. 2005. Complementing the genome with an "exposome": The outstanding challenge of environmental exposure measurement in molecular epidemiology. Cancer Epid Bio Prev. 14(8):1847–1850. Rappaport SM, Smith MT. 2010. Environment and disease risks. Science. 330(6003):460–461.

[289] *Villeneuve DL, et al. 2019. High throughput screening and environmental risk assessment – state of the science and emerging applications. Environ Toxicol Chem. 38(1):12–26.

Environment and Health lead by HGMU in the Program Environmental and Metabolic Health (ENABLE). Both, the RF E&E and the RF Health (Topic 'Environment and Health') will move biological profiling to the population level by expanding 'omics' techniques to metagenome, metaproteome and metabolome approaches.

CARF MACE takes the leadership in mainstreaming environmental assessment for complex exposure situations across different Program Topics and towards the RF Health. T9 will contribute approaches for the component of multiple chemical exposure and combined effect assessment. Use patterns of chemicals will be changing with climate change and the CARF HI-CAM on climate adaptation and mitigation as well as the CTA on extreme events will be supported by T9 on this issue. The landscape laboratory initiative of T9 will build on and contribute to the joint efforts and experiences of the observatories in the CTAs MOSES and TERENO and strives to expand these for inclusion of best management practices. For the CARF Resilient Urban Spaces, T9 will provide tools for the identification of sources of water and air pollution and effect-based monitoring strategies, e.g., for water reuse, while we need governance expertise relevant for implementation.

Transfer and contribution to SynCom. Synthesis activities are central to achieve the Program objectives. T9 in particular will contribute the developed hazard assessment concepts for objective (9). T9 will tackle the challenge of chemical pollution for providing clean water and food (7) and healthy urban spaces (5), safeguarding ecosystem services and biodiversity against unintended effects (6). T9 will support the development of more sustainable chemicals (8) by establishing criteria for degradability. The 'One Health' perspective in collaboration with the RF Health will specifically target stakeholders in disease prevention activities. T9 will contribute the translation of exposome research for knowledge communication and outreach. This comprises management of health risk factors, the utilization of diagnostic hazard tools in chemical design and development of bioeconomy products and also for future monitoring strategies. Moreover, SynCom instruments such as task force support and stakeholder dialogue can be enriched from T9 experiences in stakeholder participation which may convey solution-oriented regulation and management practice.

Table 9.1: Strategic Partners.

Name	Field of cooperation	Joint efforts
Research Networks NORMAN (norman-network.net) HBM4EU (www.hbm4eu.eu)	Human and water monitoring of chemicals	Monitoring strategy development and application cases
Children Cohort Studies LIFE Child/University of Leipzig, KUNOKids/Univ. Regensburg, KIGGS/Robert-Koch Institute/ Berlin, Generation R, Rotterdam	Continuation of mother-child cohort recruitment, integration of medical and environmental exposure perspectives	Establishing an exposome approach in the context of other potential stressors such as social factors, behavior, allergens
Enterprises e.g., L'Oréal, Bayer, Veolia	Non-animal testing strategies	Protocol development for regulatory testing and surveillance monitoring
Federal Research Institutions UBA, BfR, US-EPA, Environment Canada	Data assessment, data accessibility; schemes for regulatory innovation	Event-based monitoring, source identification, eco-exposome case studies, data repositories
Partners in Translational Work European Environment Agency, PEER – Partnership for European Environmental Research	Status reporting, lessons learned	European water quality interpretation and mapping projects

Executive Summary

- T9 combines a unique array of scientific expertise and research infrastructures to advance understanding, assessment and management of the interaction between environmental pollution and human and ecological health in a changing environment. The complexity of assessing hazards caused by mixtures of chemicals will be addressed using a structured approach that builds on comprehensive exposure measures, cause-effect relationships and identification of commonalities in exposure, degradation and mechanisms of toxicity. The research will innovate prospective risk assessment and environmental quality assessment by identifying which chemicals pose emerging risks and how their adverse effects can be anticipated and mitigated.
- The research of T9 will contribute to the Program objectives by developing coherent pollution assessment concepts (objective 9), by assessing the role of chemical burden with regard to providing healthy urban space (5), assuring clean water and food (7), safeguarding ecosystem services and biodiversity against unintended effects (6), and by establishing criteria for degradability as a driver for more sustainable new chemicals (8).
- The role of T9 in the Program is to develop tools to overcome the currently fragmented approaches in human and environmental risk assessment. By establishing an exposome perspective it will help to assure sustainable resource utilization. This promises new options for solution-oriented management strategies to support sustainable bioeconomy (T7) and to devise tailored monitoring of environmental quality (T4, T5, T6). T9 will connect the RF E&E to RF Health. Being able to monitor and predict the impact of chemical pollution will help us to combat pollution and safeguard a healthy planet.

List of Abbreviations and Acronyms

*	Symbol indicating publications of Program members, see footnotes of Topic texts
[UC]²	Urban climate model and observation program, BMBF program
79NG	79 North Glacier
AAD	Australian Antarctic Division
AARI	Arctic and Antarctic Research Institute, Russia
ABC/J	Geoscientific network of the Aachen-Bonn-Cologne/Jülich research area
ACC	Antarctic Circumpolar Current
ACE-FTS	Atmospheric Chemistry Experiment with a Fourier Transform Spectrometer
ACROSS	Advanced Remote Sensing – Ground-Truth Demo and Test Facilities, Helmholtz-funded project operated by KIT
ACTRIS-D	Aerosols, Clouds and Trace Gases Research Infrastructure, on ESFRI Roadmap
ADNT	Amino Dinitrotoluene
ADVANTAGE	Advanced Technologies for Navigation and Geodesy, Helmholtz-funded project operated by DLR and GFZ
AEI	Albert Einstein Institute, Max Planck Institute for Gravitational Physics
AeroHEALTH	Helmholtz International Laboratory
AGRASIM	Agricultural Mesocoms Facility
AI	Artificial Intelligence
AIDA	Aerosol Interaction and Dynamics in the Atmosphere, KIT Infrastructure
AIDA-dynamics	Expansion of AIDA
AIM	Local HAICU hub, hosted at HZG
AIMES	Analysis, Integration and Modelling of the Earth System, global research project of Future Earth
AIRS	Atmospheric Infrared Sounder
ALE	Adaptive Laboratory Evolution
ALOIS	Arctic Lithosphere-Ocean Interaction Study
AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
ANDRA	Agence nationale pour la gestion des déchets, French national radioactive waste management agency
AON	Aon Weather & Climate Risk Innovation Network
AOP	Adverse Outcome Pathway
API	Application Programming Interface
APPLICATE	Advanced Prediction in Polar regions and beyond: Modelling, observing system design and LInkages associated with ArctiC ClimATE change, EU Horizon 2020 project
AR/VR	Augmented Reality/Virtual Reality
ARCHES	Autonomous Robotic Networks to Help Modern Societies, PoF IV CARF
ARIM	Autonomous Robotic sea-floor Infrastructure for bentho-pelagic Monitoring
ASEAN	Association of Southeast Asian Nations
ASSEMBLE	Association of European Marine Biological Research Laboratories Expanded
ASTAR	Arctic Study of Tropospheric Aerosol and Radiation
ATAL	Asian Tropopause Aerosol Layer
ATMO/ATMO-KIT	Atmosphere and Climate, Helmholtz Program in PoF III
ATMO-HUB	Atmospheric Data Management Hub in RF E&E
AtmoSat	Satellite for Atmospheric Research, planned
ATMOsense	Helmholtz Strategic Development Investment, planned for submission
ATWAICE	ATlantic WAter pathways to the ICE in the Nansen Basin and Fram Strait
AUV	Autonomous Underwater Vehicle
AVT	RWTH Aachen Process Engineering

AWI	Alfred-Wegener-Institut, Helmholtz Centre for Polar and Marine Research, Bremerhaven, member of the Helmholtz Association
AWI-CM	AWI Climate Model
AWIPEV	Land Station of AWI, Spitzbergen
BAH	Biologische Anstalt Helgoland, Biological Institute Helgoland
BAS	British Antarctic Survey
BAW	Bundesanstalt für Wasserbau, German Federal Waterways Engineering and Research Institute
BBK	Bundesamt für Bevölkerungsschutz und Katastrophenhilfe, German Federal Office of Civil Protection and Disaster Assistance
BDC	Brewer-Dobson Circulation
BDZ	Bildungs- und Demonstrationszentrum e.V. Dezentrale Infrastruktur
BENDER	Benthos-Informationssystem in der Nordsee für Umweltmanagement und -forschung
BESTMAP	Behavioural, Ecological and Socio-economic Tools for Modelling Agricultural Policy, EU project
BfG	Bundesanstalt für Gewässerkunde, German Federal Institute of Hydrology
BfN	Bundesamt für Naturschutz, German Federal Agency for Nature Conservation
BfR	Bundesinstitut für Risikobewertung, German Federal Institute for Risk Assessment
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe, German Federal Institute for Geosciences and Natural Resources
BGS	British Geological Survey
BioLIQ	Biomass-to-Liquids Conversion Process ®
BioSC	Bioeconomy Science Centre
BKG	Bundesamt für Kartographie und Geodäsie, German Federal Agency on Cartography and Geodesy (BKG)
BMBF	Bundesministerium für Bildung und Forschung, German Federal Ministry of Education and Research
BmE	Bioeconomy meets Energy, PoF IV CARF
BonaRes	Soil science network: Soil as a sustainable resource for the bioeconomy, BMBF-funded initiative
BREED-FACE	Free Air Carbondioxide Enrichment Infrastructure for Breeding
BRGM	French Geological and Mining Research Bureau
BSH	Bundesamt für Seeschifffahrt und Hydrographie, German Federal Maritime and Hydrographic Agency
BSRN	Baseline Surface Radiation Network
BUW	Bergische Universität Wuppertal, University of Wuppertal
CAD	Computer Aided Design
CAIAG	Central Asian Institute for Applied Geosciences
CAMS	Copernicus Atmospheric Monitoring Services
CAP	European Common Agricultural Policy
CARF	Cooperation across Research Fields
CARIBIC	Civil aircraft for the regular investigation of the atmosphere based on an instrument container, KIT infrastructure associated with IAGOS (see there)
CAS	Chinese Academy of Sciences
CAU	Christian-Albrechts Universität Kiel, Kiel University
CCA	Cross-Cutting Activity
CCAMLR	Conservation of Antarctic Marine Living Resources
CCGA	Competence Centre Genomic Analysis
CCZ	Clarion Clipperton Zone
CEBITEC	Center for Biotechnology Bielefeld University
CEDIM	Center for Disaster Management and Risk Reduction Technology, KIT
CEH	Centre for Ecology & Hydrology, UK
CEN	Center for Earth System Research & Sustainability, Universität Hamburg
CEPLAS	Cluster of Excellence on Plant Sciences, DFG-funded
CGIAR-Institutes	Consultative Group on International Agricultural Research – Institutes, including CIAT, ILRI and IRRI

CHAMP	Challenging Minisatellite Payload
CIAT	International Center for Tropical Agriculture, Colombia, a CGIAR Institute
CITEpro	CITEPro: Chemicals In The Environment-Profiler, (bio)analytical platform for a high-throughput screening of chemicals and environmental samples, operated by UFZ
CLaMS	Chemical Lagrangian Model of the Stratosphere
CLIB2021	Cluster Industrielle Biotechnologie e.V.
CliCCS	Climate, Climatic Change, and Society, Cluster of Excellence, DFG-funded
ClimXtreme	Climate Change and Extreme Events, BMBF Funding Priority
CMEMS	Copernicus Marine Environment Monitoring Service
CMIP	Coupled Model Intercomparison Project of the WCRP
CMIP6	Climate Model Intercomparison Project 6 for IPCC
CNR-IGG	National Research Council of Italy for Geosciences and Earth Resources
COPERNICUS	European Earth Observation Program
CORDEX	Coordinated Regional Climate Downscaling Experiment
COSMIC-1/2	Constellation Observing System for Meteorology, Ionosphere, and Climate - Joint Taiwan-U.S. satellites
COSMO-ART	COSMO-Aerosols and Reactive Trace Species Module
COSMUS	Continental Shelf Multidisciplinary flux Study
COSPAR	Committee of Space Research
COSYNA	Coastal Observing System for Northern and Arctic Seas
CRISPR-Cas	Clustered Regularly Interspaced Short Palindromic Repeats/CRISPR associated nucleases, tool for genetic engineering
CrossInn	Cross-valley flow in the Inn Valley, investigated by dual-Doppler-Lidar Measurements
CryoSat	ESA satellite mission to monitor the thickness of land ice and sea ice
CSM	Centre Scientifique de Monaco
CSMP++	Finite element and finite volume base code
CSP	Climate Service Partnership
CTA	Cross-Topic Activity
CTBTO	Comprehensive Test Ban Treaty Organization
CVOO	Cape Verde Ocean Observatory
CZEN	Critical Zone Exploration Network
CZO	Critical Zone Observatories
D	Deliverable
DACCIWA	Dynamics-Aerosol-Chemistry-Cloud Interactions over West Africa, EU-funded project
DAM	Deutsche Allianz für Meeresforschung – German Alliance of Marine Research
DANUBIUS-RI (ESFRI)	International Centre for Advanced Studies on River-Sea Systems
DAS	Distributed Acoustic Sensing
DBFZ	Deutsches Biomasseforschungszentrum, German Biomass Research Center
DE	Digital Earth, CTA of the RF E&E
de.NBI	German National Bioinformatics Infrastructure
DECOVALEX	DEvelopment of COupled models and their VALidation against Experiments, Benchmarking Project
DEPAS	Deutscher Geräte-Pool für amphibische Seismologie, German instrument pool for amphibian seismology
DESA	Deutsche ErdSystem Allianz – German Earth System Alliance
DESTRESS	Demonstration of soft stimulation treatments of geothermal reservoirs, EU Horizon 2020 project
DESY	Deutsches Elektronen-Synchrotron, Hamburg, member of the Helmholtz Association
DFG	Deutsche Forschungsgemeinschaft, German Research Foundation
DFO	Department of Fisheries and Oceans, Canada
DIC	Dissolved Inorganic Carbon
DKK	Deutsches Klima-Konsortium, German Climate Consortium
DKRZ	Deutsches Klimarechenzentrum, German Climate Computing Centre

DKRZ-CERA-WDCC	Data Portal CERA of the World Data Center for Climate, hosted by the German Climate Computing Center
DL	Deep Learning
DLR	Deutsches Zentrum für Luft- und Raumfahrt, German Aerospace Center, Köln, member of the Helmholtz Association
DLR-IPA	DLR Institute for Physics of the Atmosphere
DLR-SO	DLR Institute of Solar-Terrestrial Physics
DOI	Digital Objective Identifier
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DPPN	German Plant Phenotyping Network
DROMLAN	Dronning Maud Land Air Network
DWD	Deutscher Wetterdienst, German Meteorological Service
EAIS	East Antarctic Ice Sheet
EAISE	East Antarctic Ice Sheet Expeditions
EAWAG	Swiss Federal Institute of Aquatic Science and Technology
ECHAM	Atmospheric General Circulation Model
ECMWF	European Centre for Medium-Range Weather Forecast, UK
ECRA	European Climate Research Alliance
EDEN ISS	Ground Demonstration of Plant Cultivation Technologies for Safe Food Production in Space
EEA	European Environmental Agency
EERA	European Energy Research Alliance
EEV	Essential Ecosystem Variables
EIDA	European Integrated Data Archive within the European Plate Observing System
EIS	Expedition Interface System
ELIXR (ESFRI)	Distributed infrastructure for life-science information
eLTER (ESFRI)	Integrated European Long-Term Ecosystem & Socio-Ecological Research Infrastructure
EMAC	ECHAM/MESSy Atmospheric Chemistry Model
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária, Brasilian Research Organisation
EMBRC	European Marine Biological Resource Centre
EMODnet	European Marine Observation and Data Network
EMPHASIS (ESFRI)	Effective Management of Pests and Harmful Alien Species – Integrated Solutions
EMPHASIS	European Infrastructure for Multi-Scale Plant Phenomics and Simulation
ENABLE	Environmental and Metabolic Health, Program of the RF Health in PoF IV
EnMAP	Environmental Mapping and Analysis Program
ENSI	Swiss Federal Nuclear Safety Inspectorate
ENSO	El Niño-Southern Oscillation
Envisat	Environmental Satellite of the European Space Agency (out of commission)
ENVRI-FAIR	Environmental Research Infrastructures Building FAIR Services Assessment for Society, EU-funded project
EO	Earth Observation
EOS	Earth Observatory of Singapore
EOSC	European Open Science Cloud, European Research Infrastructure Consortium
EPA	Environmental Protection Agency, USA
EPICA	European Ice Core from Antarctica
EPOS (ESFRI)	European Plate Observing System
EPPN	European Plant Phenotyping Network
ERA-5	European Research Agenda 5
ERC	European Research Council
ERI	Earthquake Research Institute, University of Tokyo, Japan
ERIC	European Research Infrastructure Consortium
ESA	European Space Agency

ESD	Energy System Design, Program of the RF Energy in PoF IV
ESFRI	European Strategy Forum of Research Infrastructures
ESGF	Earth System Grid Federation
ESKP	Earth System Knowledge Platform
ESM	Advanced Earth System Modeling Capacity, CTA of the RF E&E
ESSD	Earth System Science Data
ESV	Essential Soil Variables
ETC-ICM	European Topic Centre on Inland, Coastal and Marine waters
EU	European Union
EuPLEx	European Polar Stratospheric Cloud and Lee-wave Experiment
EURAD	European Joint Research Program for Management and Disposal of Radioactive Waste
EURAD-IM	Rhenish Institute for Environmental Research at the University of Cologne
EUROCHAMP	Integration of European Simulation Chambers for Investigating Atmospheric Processes, EU-funded project
EuroGOOS	European Global Ocean Observing System, experimental study of ecological processes in coastal and shelf waters
FACS	Fluorescence-Activated Cell Sorting
FAIR	Findable, Accessible, Interoperable, Re-usable, principles governing data archival and distribution
FAO	Food and Agriculture Organization of the United Nations
FDSN	International Federation of Digital Seismograph Networks
FESOM	Finite-Element/Volume Sea Ice Ocean Model
FESOM-RecoM	Finite Element/Volume Sea Ice Ocean Model – Regulated Ecosystem Model
FIS	Forschungsinfrastrukturen, Research Infrastructures
FISH	Fluorescence In Situ Hybridization
FLEX	Fluorescence Explorer; ESA-Earth Explorer satellite mission
FLUXcube	Instrumentation for vertical profiling of turbulent fluxes
FLUXNET	Global association of greenhouse gas flux observation networks
FOCI	Flexible Ocean Climate Infrastructure
FONA	Forschung für Nachhaltige Entwicklung, Research for Sustainable Development, BMBF program
FoPoZ	Forschungspolitische Ziele, Strategic Guidelines BMBF
FORMIND	Individual-Based Vegetation Model for Forests
FP7	7th EU Framework Program for Research and Technological Development
FRAM	Frontiers in Arctic Marine Monitoring, Arctic long-term observatory
FRET	Förster Resonance Energy Transfer
FRIS	Filchner-Ronne Ice Shelf
FTE	Full-Time Equivalents
FT-ICR-MS	Fourier Transform-Ion Cyclotron Resonance-Mass Spectrometer
FTIR	Fourier Transform Infrared Spectroscopy
FU Berlin	Freie Universität Berlin
FZJ	Forschungszentrum Jülich, Research Center Jülich, member of the Helmholtz Association
GAW	Global Atmospheric Watch
GCEF	Global Change Experimental Facility, operated by UFZ
GCM	General Circulation Model
GCOAST	Geesthacht Coastal Model Framework
GCOS	Global Climate Observing System
GDR	German Democratic Republic
GEIA	Global Emissions InitiAtive
GEISER	Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs
GEM	Global Earthquake Model
GEMex	Cooperation in Geothermal energy research Europe-Mexico for development of Enhanced Geo-

	thermal Systems and Superhot Geothermal Systems, EU-funded project
Geo.X	Research Network for Geosciences in Berlin and Potsdam
GEO:N	Geoscience for Sustainability Program, BMBF-funded
GeoBioLab	Helmholtz Laboratory for Integrated Geoscientific Biological Research, operated by GFZ
GEOFON	Geoforschungsnetz, global seismological broad-band network
GeoLaB	Geothermal Laboratory in the Crystalline Basement, Helmholtz Strategic Development Investment, application submitted
GEOMAR	GEOMAR Helmholtz Centre for Ocean Research, Kiel, member of the Helmholtz Association
GEOPHYSICA	High Altitude Research Aircraft M55, Russian operated
GeoSEAs	Ocean-bottom GPS network
GEOTRACES	International Study of the Marine Biogeochemical Cycles of Trace Elements and their Isotopes
GERICS	Climate Service Center Germany at HZG
GEROS-ISS	GNSS Reflectometry, Radio Occultation and Scatterometry aboard the International Space Station
GEWEX	Global Energy and Water Exchanges project of the World Climate Research Project
GFZ	German Research Centre for Geoscience GFZ, Potsdam, member of the Helmholtz Association
GGOS	Global Geodetic Observing System
GHG	Greenhouse Gases
GIA	Glacial Isostatic Adjustment
GINR	Greenland Institute of Natural Resources
GIPP	Geophysical Instrument Pool Potsdam, GFZ Infrastructure
GIS	Geographic Information System
GITEWS	German Indonesian Tsunami Early Warning System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit, German Corporation for International Cooperation
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema, Global Positioning System
GLORIA	Gimballed Limb Observer for Radiance Imaging of the Atmosphere
GLORIA-B	GLORIA on Balloon
GNC	German National Cohort
GNSS	Global Navigation Satellite System
GOCE	Gravity field and steady-state Ocean Circulation Explorer, ESA satellite
GOLEM	Modeling platform
GONAF	Geophysical borehole Observatory at the North Anatolian Fault
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment, joint US/German gravity field space mission
GRACE-FO	Gravity Recovery and Climate Experiment – Follow-On, joint US/German gravity field space mission
GravIS	Gravity Information Service
GROW	Water as a Global Resource, BMBF Funding Priority
GRRT	Global Risk Report
GRUAN	The Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN)
GTM	Global Tsunami Model
GTS	Global Telecommunication System
HAF	Helmholtz Analytics Framework
HAFOS	Hybrid Antarctic Float Observation System
HAICU	Helmholtz Artificial Intelligence Cooperation Unit, Incubator Project
HAICU-AIM	Local HAICU hub Artificial Intelligence innovates Earth System Analytics and Modelling
HALO	High-Altitude and Long-Distance, Research Aircraft
HBI	Highly Branched Isoprenoid biomarkers
HBM4EU	European Human Biomonitoring Initiative, EU-funded project

HCDC	Helmholtz Coastal Data Center at HZG
HD(CP)²	High Definition Clouds and Precipitation for Advanced Climate Prediction, BMBF Research Initiative
HEIBRiDS	Helmholtz Einstein International Berlin Research School in Data Science
HELCOM	Baltic Marine Environment Protection Commission (Helsinki Commission)
HELGES	Helmholtz Laboratory of the Geochemistry of the Earth Surface
HGF	Helmholtz-Gemeinschaft Deutscher Forschungszentren, Helmholtz Association of German Research Centers
HI-CAM	Helmholtz Initiative on Climate Adaptation and Mitigation
HICSS	Helmholtz-Institute Climate Service Science
HIDA	Helmholtz Information & Data Science Academy, Incubator Project
HIFIS	Helmholtz Federated ID Services
HIFMB	Helmholtz Institute for Functional Marine Biodiversity
High ResMIP	High-resolution Model Intercomparison Project
HIP	Helmholtz Imaging Platform, Incubator Project
HI-Weather	High Impact Weather Project
HLRN	North-German Supercomputing Alliance
HMGU	Helmholtz Zentrum München, the German Research Center for Environmental Health, member of the Helmholtz Association
HOM	Highly Oxidized Molecules
HPA	Hamburg Port Authority
HPC	High-Performance Computing
HP-PS	Helmholtz Partnership for Plant Sciences
HPSC	High-Performance Scientific Computing
HT(S)	High-Throughput (Screening)
HT2_salt	Fluid property code
HU Berlin	Humboldt-Universität zu Berlin
HZDR	Helmholtz Centre Dresden-Rossendorf, member of the Helmholtz Association
HZG	Helmholtz Zentrum Geesthacht - Centre for Materials and Coastal Research, member of the Helmholtz Association
HZG/IfK	Institute of Coastal Research at HZG
IABP	International Arctic Buoy Programs
IAG	International Association of Geodesy
IAGA	International Association of Geomagnetism and Aeronomy
IAGOS (ESFRI)	In-service Aircraft for a Global Observing System, EU-/BMBF-funded Joint Research and Infrastructure Project
IAGOS-CARIBIC	CARIBIC Component of IAGOS
IAGOS-CORE	CORE Component of IAGOS
IAMAS	International Association of Meteorology and Atmospheric Sciences
IASPEI	International Association of Seismology and Physics of the Earth's Interior
IBISBA	Industrial Biotechnology Innovation and Synthetic Biology Accelerator
ICDP	International Continental Drilling Program
ICED	Integrating Climate and Ecosystem Dynamics in the Southern Ocean
ICES	International Council for the Exploration of the Sea
ICG/IOTWMS	Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System
ICG/NEAMTWS	Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-Eastern Atlantic, the Mediterranean and connected seas
ICGEM	International Center for Global Earth Models
ICON	Icosahedral Non-hydrostatic General Circulation Model
ICON-ART	ICON-Activity Aerosols and Reactive Trace Species
ICON-CLM	ICON-Activity Climate Limited-area Modelling

ICON-ESM	ICON-Activity Earth System Model
ICON-LAM	ICON-Activity Limited-Area-Modus
ICON-LEM	ICON-Activity Large Eddy Model
ICOS	Integrated Carbon Observation System, EU-/BMBF-funded Joint Research and Infrastructure Project
iCROSS	Integrity of nuclear waste repository systems – Cross-scale system understanding and analysis, BMBF- and Helmholtz-funded project
ICS	International Council for Science
ICSU	International Council for Science, formerly International Council of Scientific Unions
iDiv	German Centre for Integrative Biodiversity Research, Halle-Jena-Leipzig
IDS	International DORIS Service
IFM-GEOMAR	Leibniz Institute of Marine Sciences (2004-2011), since 2012 IFM-GEOMAR became the GEOMAR Helmholtz Center for Ocean Research Kiel
Ifremer	Institut français de recherche pour l'exploitation de la mer, French Research Institute for Exploitation of the Sea
IGAC	International Global Atmospheric Chemistry
IGBP	International Geosphere-Biosphere Program
I-GET	Integrated Geophysical Exploration Technologies project
IGETS	International Geodynamics and Earth Tide Service
IGS	International GNSS Service
IIT	Indian Institutes of Technology
ILEAPS	Integrated Land Ecosystem-Atmosphere Processes Study, an IGBP/FutureEarth project
ILRI	International Lifestock Research Institute, Kenya, a CGIAR Institute
ILRS	International Laser Ranging Service
IMARE	Institute for Marine Resources
IMK	Institute of Meteorology and Climate Research at KIT
IMK-AAF	IMK Department of Atmospheric Aerosol Research
IMK-ASF	IMK Department of Atmospheric Trace Constituents and Remote Sensing
IMK-IFU	IMK Department of Atmospheric Environmental Research
IMK-TRO	IMK Department of Troposphere Research
IMTA	Integrated Multi-Trophic Aquaculture
INGV	Istituto Nazionale di Geofisica e Vulcanologia, National Institute of Geophysics and Volcanology, Italy
IN-MHEWS	International Network for Multi-Hazard Early Warning System
InSAR	Interferometric Synthetic Aperture Radar
INSIDE CLOUDS	KIT Infrastructure for cloud research
INSPIRE	Infrastructure for Spatial Information in Europe
INTAROS	INTAROS: Integrated Arctic Observation System
INTERMAGNET	International Real-time Magnetic Observatory Network
IOCAS	Institute of Oceanology Chinese Academy of Sciences
IOC-UNESCO	The Intergovernmental Oceanographic Commission of UNESCO
IODP	Integrated Ocean Drilling Program
IOW	Leibniz Institut für Ostseeforschung Warnemünde, Leibniz Institute for Baltic Sea Research Warnemünde
IPAB	International Program for Antarctic Buoys
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPGP	Institute Physique de Globe Paris
IPP	Industry Partnership Program
IPPN	International Plant Phenotyping Network
IQOE	International Quiet Ocean Experiment
IRRI	International Rice Research Institute, Philippines, a CGIAR Institute

ISA	International Seabed Authority
ISC-3	International Sustainable Chemistry Collaborative Centre
ISDC	Information System and Data Center
ISMC	International Soil Modelling Consortium
iSOR	Iceland GeoSurvey
ISSI	International Space Science Institute
ITGC	International Thwaites Glacier Collaboration
ITRF	International Terrestrial Reference Frame
IVS	International VLBI Service for Geodesy and Astrometry
JERICO	Joint European Research Infrastructure for Coastal Observation
JL-ExaESM	Joint Lab Exascale Earth System Modeling
JMPC	Jülich Microbial Phenotyping Center
JOYCE	Jülich Observatory for Cloud Evolution
JPI Climate	EU Joint Programming Initiative 'Connecting Climate Knowledge for Europe'
JPI Oceans	EU Joint Programming Initiative 'Healthy and Productive Seas and Oceans'
JPL	Jet Propulsion Laboratory
JPPC	Jülich Plant Phenotyping Center
JSC	Jülich Supercomputing Center
JULIAC FZJ	Project with SAPHIR
KDM	Konsortium Deutsche Meeresforschung, Consortium of German Marine Research
KfW	Kreditanstalt für Wiederaufbau, German state-owned development bank
KIMOCC	Kiel Marine Organism Culture Centre
KIT	Karlsruhe Institute of Technology, The Research University in the Helmholtz Association
KITCube	Karlsruhe Observatory for Convection Studies
KOSMOS	Kiel Off-Shore Mesocosms for Ocean Simulations
KT	Knowledge Transfer
KTB	German continental deep drilling program
KTT	Knowledge and Technology Transfer
KüNO	Verbund Deutsche Küstenforschung – Nordsee und Ostsee, joint research program encompassing twelve collaborative projects in coastal and shelf research in the North and Baltic Sea, BMBF-funded
LandscapeDNDC	Biogeochemistry and ecosystem dynamics model
LandTrans AGRI	Modular simulator for agricultural landscapes under transition
LandTrans	Modular Simulator of Transitions for sustainable multifunctional landscapes of the future
LGGE	Laboratoire de Glaciologie et Géophysique de l'Environnement, France
LKI	Leistungskategorie 1, Helmholtz category (of activities) I = in-house research
LKII	Leistungskategorie 2, Helmholtz category (of activities) II = operation of Large-Scale Infrastructures/Facilities
LOD	Linked open data
LPJ-GUESS	Lund-Potsdam-Jena, General Ecosystem Simulator, dynamic vegetation model
LRTAP	Convention on Long-Range Transboundary Air Pollution
LTER	Long-Term Ecosystem Research
LTO	Long-Term Observatory
LUCAS	Land Use and Climate Across Scales
LUV4C	Land Use Change: Assessing the Wet Climate Forcing, and Options for Climate Change Mitigation and Adaptation, EU-funded project
LYNX	Modeling platform
M	Milestone
MACE	Mainstreaming Environmental Assessment for Complex Exposure, PoF IV CARF
MARCOPOLI	Marine, Coastal and Polar Systems, Research Programme (2004–2008)
MarDATA	Helmholtz School for Marine Data Science
MARE:N	Coastal, Marine and Polar Research for Sustainability Program, BMBF-funded

MARUM	Marine Environmental Research Center, Bremen
MATRIX	New Multi-Hazard and Multi-Risk Assessment Methods for Europe
MB	Management Board of the RF E&E
MBA	Marine Biological Association
MCM	Mass Change Mission, Helmholtz Strategic Development Investment, planned for submission
MESI	Modular Earth Science Infrastructure, umbrella for GFZ research infrastructure
MetaPro	Metabolomic Profiler, central bioinformatics and omics platform at UFZ
MFL	Marginal Field Labs
mHM	Mesoscale Hydrologic Model
MiBioLab	Microbial Bioprocess Lab; Helmholtz Innovation Lab
MICADAS	Mini Carbon Dating System
MiKaT	Mitteldeutsches Zentrum für Biokatalyse Dresden-Halle-Leipzig, Center for Biocatalysis
MIKLIP	Medium-Term Climate Prediction, BMBF-funded project
MIP	Model Intercomparison Project
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MIS	Marine Isotope Stage
ML	Machine Learning
MLS	Microwave Limb Sounder
MOBICOS	Mobile Aquatic Mesocosms, Experimental Container operated by UFZ
MOOC	Massive Open Online Courses
MOP	Mobility Panel
MOSAiC	Multidisciplinary Drifting Observatory of the Study of Arctic Climate
MOSES	Modular Observation Solutions for Earth Systems, an observing system of the Helmholtz Association and a CTA of the RF E&E
MoU	Memorandum of Understanding
MPA	Marine Protected Areas
MPAS	Model for Prediction Across Scales, global community climate model
MPI	Max Planck Institute
MPI-M	Max Planck Institute for Meteorology
MS	Marine Stations
MS	Mass Spectrometry
MSFD	Marine Strategy Framework Directive of European Union
MSP	Marine Spatial Planning
MTET	Materials and Processes for the Energy Transition, Program of the RF Energy
MTS	Department Maritime Systems, University of Rostock
MUSE	Marine Umweltrobotik und -Sensorik für nachhaltige Erforschung und Management der Küsten, Meere und Polarregionen; Helmholtz Strategic Development Investment, application submitted
mWQM	multiscale Water Quality Model
NAKO	Nationale Kohorte, German National Cohort (GNC)
NASA	National Aeronautics and Space Administration, USA
NATO	North Atlantic Treaty Organization
NCAR	National Center for Atmospheric Research, USA
NDACC	Network for the Detection of Atmospheric Composition Change
NEGIS	North-East Greenland Ice Stream
NEID	National Research Institute for Earth Science and Disaster Resilience, Japan
NEMO	Nucleus for European Modelling of the Ocean
NEMO-AGRIF	A high-resolution grid nested into a global model at coarser resolution (NEMO with AGRIF)
NERC	Natural Environment Research Council, UK
NEROGRAV	New Refined Observations of Climate Change from Spaceborne Gravity Missions, DFG-funded project
NERSC	National Energy Research Scientific Computing Center, USA

NFDI	Nationale Forschungsdateninfrastruktur, National Research Data Infrastructure
NFDI4Earth	National Research Data Infrastructure for Earth System Research
NF-POGO CofE	Nippon Foundation Partnership for Observation of the Global Ocean Centre of Excellence
NGO	Non-governmental organization
NGP²	Next Generation Processing and Products, Pilot Biorefinery at RWTH Aachen
NIEHS	National Institute of Environmental Health Sciences, USA
NIOZ	Koninklijk Nederlands Instituut voor Onderzoek der Zee, Royal Netherlands Institute for Sea Research
NMR	Nuclear Magnetic Resonance
NOAA	National Oceanic and Atmospheric Administration, USA
NOC	National Oceanography Centre, UK
NORMAN	Network of reference laboratories, research centres and related organisations for monitoring of emerging environmental substances
NS	Neumayer Station III
NSF	National Science Foundation, USA
NSTDA	National Science and Technology Development Agency of Thailand
NUNATARYUK	EU-funded Project on permafrost and social impact, coordinated by AWI
NUSAFE	Nuclear Waste Management, Safety, and Radiation Research, Program within RF Energy
NWKLN	Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz, Lower Saxon State Department for Waterway, Coastal and Nature Conservation
O2A	Observation to Archive
OBH	Ocean Bottom Hydrophones
OBS	Ocean Bottom Seismometers
ODP	Ocean Discovery Program
OECD	Organisation for Economic Co-operation and Development
OECM	Other Effective Conservation Measures
OFEG	Ocean Facilities Exchange Group
Open IFS	Open Integrated Forecasting System
OpenGeoSys	Open-source initiative for numerical simulation
ORFEUS	Observatories & Research Facilities for European Seismology
OrganCat	Conversion Process
OSCM	Ocean Science Center Mindelo, Cape Verde
OSIRIS	Optimized Strategies for Risk Assessment of Industrial Chemicals through Integration of Non-Test and Test Information, EU-funded project
OSNAP	Overturning in the Subpolar North Atlantic Program
OSSE	Observation System Simulation Experiments
PACES II	Polar regions And Coasts in the changing Earth System, Helmholtz Program in PoF III
PALAOA	Perennial Acoustic Observatory in the Antarctic Ocean
PALM	Parallelized Large-Eddy Simulation Model
PALM-4U	PALM Module for Urban Research
PalMod	Paleo Modelling – From the Last Interglacial to the Anthropocene – Modeling a Complete Glacial Cycle, German Climate Modeling Initiative, BMBF-funded project
PAMARCMiP	Polar Airborne Measurements and Arctic Regional Climate Model Simulation Project
PAMIP	Polar Amplification Model Intercomparison
PANABIO	PAN-Arctic Information System on Arctic Biota
PANGAEA	Data Publisher for Earth & Environmental Science
PB	Program Board of the Program 'Changing Earth – Sustaining our Future' (RF E&E)
PBO	Plate Boundary Observatory
PBTK	Physiologically Based Toxicokinetic
PDAF	Parallel Data Assimilation Framework
PEER	Partnership for European Environmental Research

PEGASOS	Pan-European Gas-AeroSOls climate interaction study, EU-funded project
PET	Positron Emission Tomography
PGE	Platinum-group elements
PhenoRob	Robotics and Phenotyping for Sustainable Crop Production, Cluster of Excellence, DFG-funded project
PICE	Physics of Ice, Climate and Earth
PID	Persistent Identifier
PIK	Potsdam-Institut für Klimafolgenforschung, Potsdam Institute for Climate Impact Research
PIRATA	Prediction and Researched Moored Array in the Atlantic
PISA	Potsdam Imaging and Spectral Analysis facility, GFZ Infrastructure
PKU	Peking University, China
PMIP	Paleoclimate Modelling Intercomparison Project
PoF	Program-oriented Funding, funding period for cross-center research programs of the Helmholtz Association
POGO	Partnership for Observation of the Global Ocean
POLinSAR	Polarimetric Interferometry Synthetic Aperture Radar
POLSTRACC	Polar Stratosphere in a Changing Climate, HALO Mission
POM	Particulate Organic Matter
PPD	Plant Primary Database
PRETTY	Passive Reflectometry and Dosimetry
PRIMAVERA	PRocess-based climate slMulation: AdVances in high-resolution modelling and European climate Risk Assessment
PRISMA	Earth observation satellite
ProVIS	Center for visualization of biochemical processes on cellular level, UFZ platform for chemical microscopy and mass spectrometry
PTB	Physical-technical Federal Agency
PU	Purdue University, USA
QBO	Quasi-Biennial-Oscillation
QIVIVE	Quantitative in vitro to in vivo extrapolation
QSAR	Quantitative Structure Activity Relationship
RA	Research Aircraft
RDPs	WMO's Research and Development Projects
RDX	Research Department Explosive
RECONCILE	Reconciliation of Essential Process Parameters for an Enhanced Predictability of Arctic Stratospheric Ozone Loss and its Climate Interactions, EU-funded project
REE	Rare Earth Elements
REEPON	Research platform with focus on marine ponds and reefs
RegIKlim	Regional Information on Action for Climate Change, BMBF-funded project
REKLIM	Regional Climate Change Initiative of the Helmholtz Association
REMO	Regional Model for Climate Modeling and Weather Forecast
REMO-NH	Non-hydrostatic Component of REMO
RF E&E	Research Field Earth & Environment
RF	Research Field
ROBEX	Robotic Exploration of Extreme Environments
ROMIC	Role of the Middle Atmosphere in Climate, BMBF Funding Priority Program
ROV	Remotely Operated Vehicle
RS	Remote Sensing
RSC	Remote Sensing Centre
RSMAS	Rosenstiehl School of Marine and Atmospheric Science, USA
RV	Research Vessel

RVHE	Research Vessel Heincke
RVPS	Research Vessel Polarstern
RWTH Aachen	Rheinisch Westfälische Technische Hochschule Aachen, RWTH Aachen University
S2S	Sub-seasonal to seasonal project
SABER	Sounding of the Atmosphere using Broadband Emission Radiometry
SAGOS	South African Geodynamic Observatory Sutherland
SAHFOS	Sir Alister Hardy Foundation for Ocean Science
SAPHIR	SAPHIR Atmosphärensimulationskammer, SAPHIR atmospheric simulation chamber, FZJ Infrastructure
SAPHIR-PLUS	Extension of SAPHIR, Plant Chamber
SAPHIR-STAR	Extension of SAPHIR, Stirred Atmospheric Flow Reactor
SAR	Synthetic Aperture Radar
SASSCAL	Southern African Science Service Center for Climate Change and Adaptive Land Management, BMBF Funding Priority
SAWAM	Seasonal Water Resources Management in Semi-arid Regions: Transfer of Regionalized Global Information to Practice, BMBF-funded project
SCaleX	Scale-crossing Land Surface and Boundary Layer Processes, joint research project
SCAR	Scientific Committee on Antarctic Research
SCC	Steinbuch Centre for Computing at KIT
SCOR-UNESCO	Scientific Committee on Ocean Research of the UNESCO
SCOSTEP	Scientific Committee on Solar-Terrestrial Physics
SCOUT-O3	Stratosphere-Climate links with emphasis on the UTLS
SDG	Sustainable Development Goals of the United Nations
sDiv	Synthesis Centre of iDiv
SENTINEL	ESA satellite program to monitor e.g., ocean surface topography, Earth's surface temperature, and ocean color
SESYNC	National Socio-Environmental Synthesis Center at the University of Maryland
SFB	Sonderforschungsbereich, Collaborative Research Center, DFG-funded
SG	Superconducting Gravimeter
SHARP	Stratospheric Change and its Role for Climate Prediction, Research Unit, DFG-funded
SHI	Spatial Heterodyne Interferometer
SIF	Solar-induced Chlorophyll Fluorescence
SIMS	Secondary Ion Mass Spectrometer
SIO	Second Institute of Oceanography, China
SLCF	Short-lived climate forcers
SLR	Satellite Laser Ranging
SMART	Science Monitoring and Reliable Telecommunications
SMART	Scalable, Mechanistic, Adapted Complexity, Robust, and Transferable
SMOS	ESA satellite mission to monitor Soil Moisture and Ocean Salinity
SO	Southern Ocean
SOA	Secondary Organic Aerosol
SOCAT	Surface Ocean CO_2 Atlas
SOLUTIONS	SOLUTIONS for present and future emerging pollutants in land and water resources management, EU-funded project
SouthTRAC	HALO Mission 2019
SPACES 2	Research partnerships for the adaptation of complex processes in the Earth system in the Southern African region, BMBF Funding Priority
SPARC	Stratospheric processes and their role in climate
SPP	Schwerpunktprogramm, Priority Program, DFG-funded
SROCC	Special IPCC Report on the Ocean and Cryosphere in a Changing Climate
ST	Subtopic

StratoClim	Stratospheric and Upper Tropospheric Processes for better Climate Predictions, EU-funded project
SUGAR	Submarine Gas Hydrate Reservoirs
SURE	Radial Water Jet Drillings, EU-funded project
SUSALPS	Sustainable Use of Alpine and Pre-alpine Grassland Soils in a Changing Climate, BMBF-funded project
SV	Sparkassen Versicherung, Sparkasse Insurance
SWARM	ESA satellite mission to study the Earth's magnetic field
SynCom	Synthesis and Communication Platform Earth and Environment
T	Topic
TANDEM-L	Planned satellite mission: two radar satellites operating in L-band (23.6 cm) wavelength
TAQA	Abu Dhabi National Energy Company
TB	Topic-Speakers Board of the RF E&E
TCCON	Total Carbon Column Observing Network, global
TD	Toxicodynamics
TEEB	The Economics of Ecosystems and Biodiversity
TEM	Transmission Electron Microscope
TEMS	Terrestrial Model Systems
TEODOOR	Data-portal of TERENO
TERENO	TERrestrial ENvironmental Observatories, a Research Infrastructure of the Helmholtz Association, CTA of the RF E&E
TERENO-preAlpine	TERENO observatory in the Bavarian Alps and pre-Alps
TerrSysMP	Terrestrial System Modeling Platform
TESSIN VISLab	Visualization Center, a high-resolution immersive virtual reality platform, operated by UFZ
TEW	Tsunami Early Warning
THMC	Thermo-Hydro-Mechanical-Chemical
THORPEX	The Observing System Research and Predictability Experiment
THW	Technisches Hilfswerk, German Federal Agency for Technical Relief
TK	Toxicokinetics
TK3	Eddy-covariance processing software
TLZ	Technology and Logistics Centre of GEOMAR
TNO	Netherlands Organisation for Applied Scientific Research
TNT	Trinitrotoluene (explosive)
TOAR	Tropospheric Ozone Assessment Report
TRL	Technology Readiness Level
TROPOS	Leibniz-Institut für Troposphärenforschung, Germany
TR-SFB	Transregio SFB, Collaborative Research Center/Transregio, DFG-funded
TT	Technology Transfer
TTO	Technology Transfer Office
TU Berlin	Technische Universität Berlin
TUD	Technical University Dresden
UAV	Unmanned Aerial/Aircraft Vehicle
UBA	Umweltbundesamt, German Federal Environment Agency
UCAR/NCAR	University Corporation for Atmospheric Research, USA
UFL	University of Florida, USA
UFZ	Helmholtz Centre for Environmental Research – UFZ, Leipzig, member of the Helmholtz Association
UN	United Nations
UNEA	United Nations Environment Assembly
UNECE-HTAP	United Nations Economic Commission for Europe - Hemispheric Transport of Air Pollution
UNEP	United Nations Environment Program, today the UN Environment
UNESCO	United Nations Educational, Scientific and Cultural Organization

UNESCO-IOC	United Nations Educational, Scientific and Cultural Organization – Intergovernmental Oceanographic Commission
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations International Strategy for Disaster Reduction
UrbENO	Urban Environmental Observatories
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UT	Upper Troposphere
UTCSR	University of Texas Center for Space Research, USA
UTLS	Upper Troposphere Lower Stratosphere
VILMA	Viscoelastic Lithosphere and Mantle model
VIMS	Virginia Institute of Marine Science, USA
VLBI	Very Long Baseline Interferometry
VLIZ	Flanders Marine Institute, Belgium
W2W	Waves to Weather, Collaborative Research Center/Transregio, DFG-funded
WAIS	West Antarctic Ice Sheet
WASCAL	West African Science Service Center on Climate Change and Adapted Land Use, BMBF Funding Priority
WBGU	Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen, German Advisory Council on Global Change
WCH	Wissenschaftscampus Halle, Science Campus Halle
WCRP	World Climate Research Program
WCRP-CORA	World Climate Research Program – Coordination Office for Regional Activities
WCRP-CORDEX	World Climate Research Program – Coordinated Regional Climate Downscaling Experiment
WCRP-SPARC	World Climate Research Program Stratosphere – Troposphere Processes and their Role in Climate
WDC	World Data Centre for Geomagnetism
WDS	World Data System
WebGIS	Web mapping with geographic information system
WESS	Water and Earth System Science; competence cluster
WFD	EU Water Framework Directive
WGMS	World Glacier Monitoring Service
WHO	World Health Organization
WHOI	Woods Hole Oceanographic Institute, USA
WISE	Wave-driven Isentropic Exchange, HALO Mission
WMO	World Meteorological Organisation
WP	Work Package
WRF	Weather Research and Forecasting model, global/regional community weather/climate model
WRF-Chem	WRF Regional Chemistry and Transport Model
WRF-Hydro	WRF Coupled Regional Climate-Hydrology Model
WSMPA	Weddell Sea Marine Protected Area
WWF	World Wide Fund for Nature
WWRP	World Weather Research Programme
YIG	Young Investigator Group
YOPP	Year of Polar Prediction
ZAF	Zentrum für Aquakulturforschung, Center for Aquaculture Research, AWI
ZALF	Leibniz Centre for Agricultural Landscape Research
Zeppelin NT	Helmholtz Research Infrastructure
ZMT	Leibniz Zentrum für Marine Tropenforschung, Leibniz Centre for Tropical Marine Research
ZUGOG	Zugspitze Geodynamic Observatory Germany

Program 'Changing Earth – Sustaining our Future'

Program Spokesperson: Hauke Harms

Participating Helmholtz Centers:

AWI Alfred Wegener Institute
Helmholtz Centre for Polar and Marine Research

FZJ Forschungszentrum Jülich GmbH

GEOMAR
Helmholtz Centre for Ocean Research Kiel

GFZ Helmholtz Centre Potsdam
German Research Centre for Geosciences

HZG Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

KIT Karlsruhe Institute of Technology

UFZ Helmholtz Centre for Environmental Research