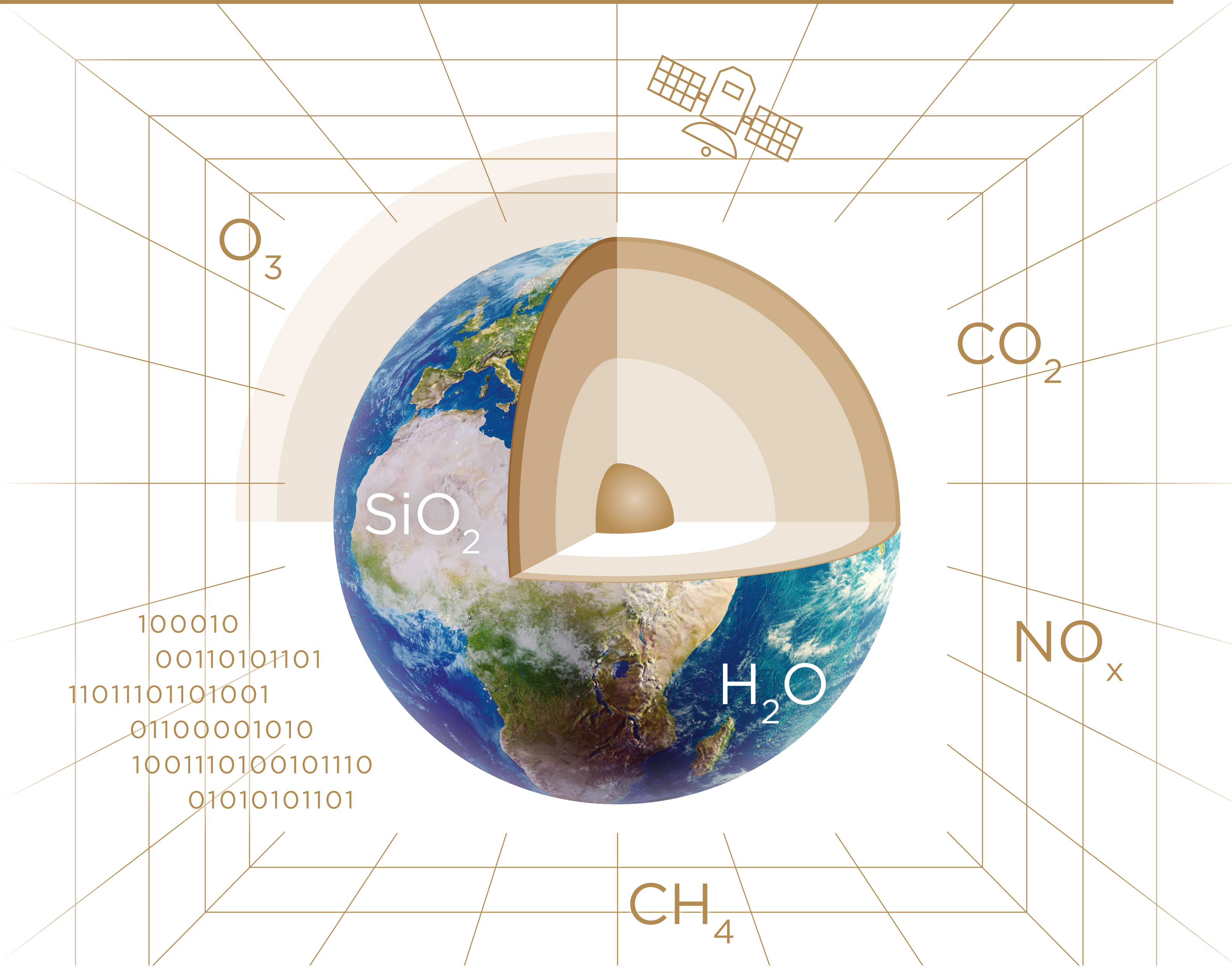
Leopoldina
Nationale Akademie
der Wissenschaften

Report on Tomorrow's Science



Earth System Science

Discovery, Diagnosis, and Solutions in Times of Global Change

Imprint

Publisher
German National Academy of Sciences Leopoldina
Deutsche Akademie der Naturforscher Leopoldina e.V.
Jägerberg 1, 06108 Halle (Saale), Germany

Editors
Prof. Dr. Onno Oncken, Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences
Prof. Dr. Friedhelm von Blanckenburg, Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences
Prof. Dr. Gerhard Wörner, University of Göttingen
Prof. Dr. Peter Schlosser, Arizona State University, Tempe (USA)

Scientific officers
Dr. Christian Anton, Johannes Mengel, Dr. Henning Steinicke, Dr. Sebastian Wetterich
German National Academy of Sciences Leopoldina
Contact: politikberatung@leopoldina.org

Editing
Ellen Kappel, Phd, Geo Prose, Bethesda, USA

Translation
Peschel Communications GmbH, Freiburg

Title graphics and Cover Design
Sisters of Design – Anja Krämer & Claudia Dölling GbR, Halle (Saale)

Graphics
Erfurth Kluger Infografik GbR, Berlin

Design and typesetting
Klötzner Company, Hamburg

Printing
druckhaus köthen GmbH & Co. KG
Friedrichstraße 11/12
06366 Köthen (Anhalt)
Germany

ISBN: 978-3-8047-4256-7

DOI
https://doi.org/10.26164/leopoldina_03_00591

Bibliographic information published by the German National Library
The German National Library lists this publication in the German National Bibliography. Detailed bibliographic data is available online at http://dnb.d-nb.de.

Recommended citation
German National Academy of Sciences Leopoldina (2022): Report on Tomorrow’s Science. Earth System Science – Discovery, Diagnosis, and Solutions in Times of Global Change. Halle (Saale).

Editorial deadline
June 30, 2022

Report on Tomorrow’s Science

Earth System Science

Discovery, Diagnosis, and Solutions in Times of Global Change

Table of contents

Foreword

Planet Earth is a complex system. The interaction and dynamics of its components shape our planet and have thus a significant influence on its habitability for humans. However, our understanding of the Earth system is incomplete. Many big questions in the Geosciences yet remain unanswered. Some of those are: Which conditions defined the origin and evolution of life on Earth? Are earthquakes reliably predictable? How long will oceans continue to buffer climate change? How do biodiversity and climate interact? Are the planet's resources sufficient to ensure the survival of the Earth's population?

Since humans massively intervened in the structure of the Earth and became a decisive force whose influence is drastically seen in all parts of the planet, it has become particularly clear how fragile the dynamics in the Earth system are. Nobel laureate Paul Crutzen ML coined the term Anthropocene for this new age of Earth history.

Humans have initiated global processes threatening the environment and living conditions of a large part of the world's population, making entire regions of the Earth uninhabitable, impairing global health and depleting natural resources to such an extent that the development of future generations is compromized. Developing the scientific basis for an understanding of these processes and for risk assessments and solutions are the central challenges of the geosciences today. This requires an approach characterized by systemic thinking – the Earth System Science.

However, the study of the Earth system also faces challenges within academia. The complexity of this field of research encounters fragmented academic training and research of a wide variety of disciplines.

This Report on Tomorrow's Science is a plea to develop Earth System Science as a conceptual and structural framework to give new impetus to basic research and to address societal challenges. It calls for questioning traditional patterns of thinking in teaching and research and building sustainable structures that meet the major challenges. This is the only way to gain the necessary understanding of the changes in our living environment and to develop appropriate science-based options for action.

Prof. (ETHZ) Dr. Gerald H. Haug

President of the German National Academy of Sciences Leopoldina

Executive Summary

The Earth System is rapidly moving towards critical thresholds as the actions of the modern industrialized societies increasingly threaten our planet's life-support systems. Human actions are jeopardizing the well-being of future generations, rendering the maintenance of Earth System stability the biggest challenge facing global society now and for the foreseeable future. Humankind must quickly develop and implement broadly acceptable solutions to mitigate climate changes; sustainably exploit resources such as food sources, raw materials, water, land, and ocean; anticipate and mitigate natural hazards in a society that is increasingly urbanized; monitor and assess critical trajectories of Earth System components. The urgent need to address these and more challenges as laid out in the UN Sustainable Development Goals elevates the Geosciences to one of the leading scientific disciplines of the future.

In recent decades, the Geosciences have pursued a more quantitative approach to conceptualising Earth processes using advanced Earth observation, monitoring, and modelling techniques. A key development has been recognition of the tight connection between Earth System components: a framework called "Earth System Science". Yet Germany has not yet fully embraced an Earth System Science approach to Geoscience in the discipline's research institutions, research topics, education, and professional societies. A shift towards Earth System Science is paramount because the societal and scientific challenges far exceed the ability of individual disciplines to find solutions.

Despite numerous positive developments and the strength of the Geosciences in German universities and non-university institutions, the German research landscape so far lacks the research and education umbrella with the capacity to address the considerable planetary challenges in all their dimensions. A young generation concerned about the myriad issues surrounding global change will increasingly find Geoscience degrees attractive. Thus, it is time to establish modern Earth System Science in Germany as a forward-looking framework that builds on the strength of established Geoscience disciplines but significantly intensifies cross-disciplinary interconnection, embraces, and promotes scientific discovery, provides a diagnosis of the state of the planet, and develops solutions to the many challenges posed by a rapidly changing world.

With this report, the German National Academy of Sciences Leopoldina aims to:

1) Initiate discussion and action among the different Geoscience disciplines and their cooperating fields regarding future scientific and organisational development within Germany, and

2) provide stakeholders with recommendations on important actions that are required.

This report identifies the following actions needed to modernize German Geosciences and ensure its leadership in providing solutions to the many challenges facing society:

I. Establish Earth System Science as the operating framework

Earth System Science is the ideal framework for understanding our planet and for resolving the numerous interactions and feedbacks within Earth's systems. It integrates and complements advances in the separate Geoscience disciplines as a prerequisite for the successful development of solutions. This Earth System Science will be more transdisciplinary, more quantitative, and more digital, taking advantage of technological advances in the natural sciences, computing, and engineering.

II. Build observation capacity

The need to detect, observe, and monitor change in Earth system parameters critical for modern human society requires massive investment in Earth observation capability, analytical tools, and infrastructure. Funding agencies, universities, and research institutions should consider jointly designing a national roadmap to build observation capacity by investing in a new generation of Earth observation and data management infrastructure. This infrastructure will enable direct and broad access to observational data and visualization tools.

III. Develop digital infrastructure/Big Data

Advancing fundamental understanding of the Earth System and ensuring a safe operating space for humankind requires identifying trajectories, boundaries, and critical thresholds of global change, resource depletion, and geohazards and how crossing these thresholds may impact society and the environment. This need requires major investment in digital scientific infrastructures that must be accompanied by initiatives for a national data strategy and high-performance computing infrastructure that includes establishing appropriate capacities for 'Big Data' storage, analysis, and modelling.

IV. Advance education

Training the next generation of geoscientists is integral to successful realisation of these ambitious plans. Curricular changes are best implemented early in schools with the aim of attracting high school students with strong interests and background in STEM (Science, Technology, Engineering and Mathematics) fields to university education in Earth System Science. Combining basic research with an orientation toward solving future problems in an Earth System context must be a cornerstone of education in all Geoscience disciplines. Curricula shall contain cross-disciplinary elements that teach students how to take advantage of the full potential of Earth observation systems and analytical tools, develop modelling strategies, and use advanced data analytics methods.

V. Develop skills for effectively communicating solutions

Communicating options for solutions to the public and policymakers is beyond the training of most Geoscience departments at universities and research centres. Effective communication of 'solution science' will require involvement of other disciplines as well as of the public, starting from the stage of defining the problem – thus developing a two-way communication. Hence, Geoscience departments need to expand their connections with other disciplines beyond the Natural Sciences and find a common language with the public.

VI. Enhance networking

Earth System Science will require the formation of networks to generate critical mass in terms of competencies, research, and infrastructure capacities to address current scientific and societal challenges. The marine sciences already have successful large-scale cross-disciplinary networks and partnerships; they are equally required in the terrestrial realm. Such networks and partnerships shall best form at the regional, national, and European scales. One added benefit is that University partners can make the best use of observation and analytical capacities operated by non-university institutions. And finally, to become leaders in the field of Geosciences, the German Geoscience societies need to develop 'one voice' towards their science, the public, and stakeholders.

1 Science for our Planet in Times of Change

1.1 The Era of the Geosciences

Many of the fundamental challenges facing humankind today are pertinent to the fields of the Geosciences[1]. Climate change, the growing demand for natural resources and the increasing vulnerability of human civilisation, its infrastructure, and the global economy have gained the attention of the general public. Flooding, sea-level rise, land degradation, drought, extreme weather events, and resource and water scarcity are just some of the many challenges facing humanity. Understanding the underlying processes while managing the consequences of these events are tasks for the future of humanity.

This realisation is accompanied by a paradigm shift in the Geosciences. Today we view the Earth as a dynamic system of interactive physical, chemical and biological processes. The aim of this report is to embed the concept of Earth system research more firmly in research and education.

That humans became a force in the Earth system has led to the suggestion of a new geologic era, the "Anthropocene." This new paradigm requires deep engagement of the Geosciences: the 17 UN Sustainable Development Goals (SDGs) aim to end global poverty, improve public health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our ocean and terrestrial ecosystems.2 Five of the SDGs have the Geosciences immediately at their heart: clean water, clean energy, climate action, life below water, and life on land. In essence, the SDGs demand that Earth resources be used without compromising the needs of future generations.

The Geosciences in Germany is in an excellent position to play a prominent role in confronting these challenges of planetary change and contributing to urgently needed solutions. The Geosciences benefit from a political system that is favourable to basic and applied science, a modern research infrastructure, and internationally highly visible research units and scientists, and there is potential to attract a young academic workforce from within Germany and beyond. One may question whether the German

---

1 Geoscience is the science of the Earth including its deep interior, continents, ocean, atmosphere, magnetosphere, rivers, groundwater, glaciers, and soils. Geoscience includes organisms that interact with Earth including humans.

2 United Nations (2015). For Germany, WBGU (2011) describes the transition to sustainability.

Geosciences are currently fully exploiting their potential. Given both the challenges and the opportunities, it should be expected that the Geosciences as a whole would be on par with the other Natural Sciences and be perceived favourably by the public. One indicator that this is not yet the case is the presence of a large group of highly motivated young people concerned about the future of our planet whose increased interest in climate or sustainability issues is not, however, reflected in rising undergraduate numbers in geoscience courses.

The aim of this report is to provide background and perspectives on the potential, opportunities, and challenges facing the Geosciences within the framework of Earth System Science.

1.2 The Fragmentation of the Geosciences

Fragmentation into Geoscience sub-fields

One inherent feature of the Geosciences in German universities is its fragmentation into small units by subdiscipline. These units range from the sciences of the Solid Earth and the planetary system (Geology, Mineralogy, Geo- and Cosmochemistry, Palaeontology, Geophysics) to the sciences of the terrestrial surface of our planet (Physical Geography, Soil Sciences, Geoecology, Hydrology, and Environmental Sciences), those of the ocean, atmosphere, and cryosphere (Oceanography, Meteorology, Glaciology; often arranged as subdisciplines of Physics), and disciplines that deal with surveying our planet (Geodesy and Remote Sensing, Geoinformatics), and Human Geography. In contrast, in English-speaking countries, these disciplines are often grouped within Earth Science departments.

University degrees in Germany reflect this organisational fragmentation to some extent, although progress has been made in the past two decades in offering a unified “Geosciences” curriculum that primarily includes the subdisciplines of the Solid Earth: (Geology, Mineralogy, Geo- and Cosmochemistry, Palaeontology, Geophysics, and their applied fields). However, an increasing number of specialized university curricula is often limited by the classical disciplinary boundaries. Degrees in “Climate System Science” or “Earth System Science” that would potentially be attractive to the concerned generation are still largely absent.

Fragmentation of the academic societies

Another characteristic of German Geosciences is the even larger fragmentation of the discipline into multiple geoscientific societies. About 25 separate societies cover the Earth Sciences in Germany. The “Solid Earth” Geosciences alone is dispersed into four major and a few minor societies although it is taught as a unified discipline in most German university curricula. As a result, German Geosciences does not possess the capacity to speak with one voice, unlike Physics or Chemistry whose subdisciplines are each organised in a single society.

Separation between universities and research centers

A structural challenge common to all scientific disciplines in Germany, including the Geosciences, is that research is conducted with different orientation and little coordination at both universities and non-university research institutions (e. g., Max Planck-, Helmholtz-, Leibniz- Society institutions) as well as at federal and state agencies. Because universities are under the sovereignty of the German “states”, a legal framework for coordination between them does not exist either. Further, the non-university Earth Science research institutes and museums, mostly operated by the federal government, are organised in the Max Planck Society, Helmholtz or Leibniz associations and governmental agencies like the Federal Institute for Geosciences and Natural Resources (BGR). Synchronisation and coordination of large research initiatives is not an integral feature of this setup, nor are these institutes’ activities necessarily aligned with university research. As a result, universities and non-university research institutions have not yet fully exploited the opportunities that this overall very successful setup provides.

Diverse labour market

The current German labour market and the spectrum of industry and employers for Geoscience graduates is no less fragmented than Germany’s Geoscience disciplines. Geo- and engineering offices, including freelance consultants, resource industries, and commercial enterprise, as well as near- and far-subject businesses in other fields, complement government agencies as the most relevant employers for graduates in Geosciences. Only about 10% of geoscientists are employed in universities and research institutions[3]. Although this heterogeneity of the labour market is not expected to fundamentally alter, the new challenges have started to exert change. The most obvious drivers of this change are the transition to renewable energy, leading to the jettisoning of employment in the fossil fuel industry; a revival of economic geology focused on metals for new energy sources; compliance with stricter environmental regulations; rapid technological advances in observational and analytical methods; consultancy in policy development; and the increasing importance of ‘Big Data’.

Challenges for the Geosciences

Given this situation, it is not surprising that the Earth Science community is now engaged in an increasingly pressing discussion about the future of the Geosciences. This discussion mainly revolves around three issues:

1) For young people, the offered Geoscience degrees appear to be diffuse in their focus and not sufficiently well-defined in their job profile and perspective.

2) Maintaining a solid base in fundamental, curiosity-driven research is essential to ensure the progress of the science. Yet today, scientists also need to increasingly engage in solving problems related to Earth’s future and the species that live on it (including humans). Merely identifying problems and refining observations that characterise them is no longer sufficient.

3) The grand challenges facing the Earth Sciences are of a dimension that cannot be solved by the classical disciplines alone. The solutions require new ways to face challenges that are inherently interdisciplinary.

Here we suggest using Earth System Science as a comprehensive, interdisciplinary, and guiding framework to enable the subdisciplines of the Geosciences to solve the global challenges humanity faces today whilst maintaining the strengths of their core subdisciplines and curiosity-driven research.

---

[3] Merschel et al. (2020).

1.3 The Earth System Approach

Key to Earth System Science is the understanding that the Earth is composed of five main spheres or systems—the geosphere, the hydrosphere (including the cryosphere), the atmosphere, the biosphere, and the anthroposphere— interconnected through material and energy fluxes (Fig. 1). Feedbacks and interactions among Earth's systems show characteristic properties of complex systems and have created conditions on Earth that make our planet habitable. For example, finely tuned negative feedbacks have sufficiently stabilized surface temperatures on Earth to enable life to evolve and thrive over billions of years.

Interactions and feedbacks between Earth's spheres

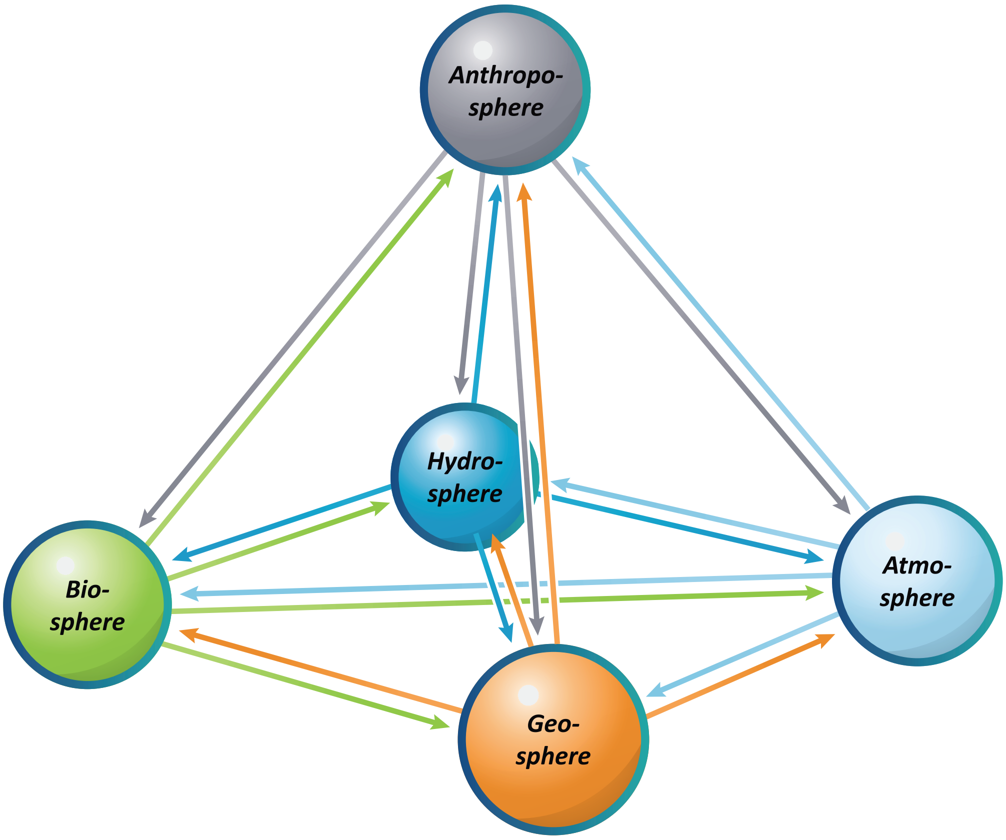


Figure 1. Conceptualising the Earth System governed by mutual interdependencies of its spheres. Today a recognized Earth System component is the Anthroposphere—the part of the environment that is made or modified by humans for use in human activities and human habitats.

Earth System Science without narrow disciplinary boundaries

By viewing Earth as a complex, interconnected system, the Earth System Science concept removes barriers between Geoscience disciplines, strengthening curiosity-driven research and the search for prognosis of and solutions for some of today's most pressing problems in a world of change. Today, many of the complex interactions among climate system components can be assessed by direct observation, resulting in an increasingly deeper understanding of these processes. In contrast, the dynamics of domains such as Earth's deep interior or the distant past remain poorly understood because incomplete records, low spatial and temporal resolution of the data, or restricted accessibility limit investigation.

A significant challenge for conducting Earth System Science is overcoming these limits to data collection. If we are to understand the Earth System, we need to examine the trajectory over which Earth developed, from its formation to its current state. This evolution encompasses a multitude of timescales, from millions of years over which plate tectonic activity such as mountain-building and subduction has exchanged materials between the deep Earth and its surface and atmosphere to tens of thousands of years to interannual or seasonal timescales over which interactions between the atmosphere, hydrosphere, cryosphere, and biosphere modify Earth's climate.

Because today humans are such powerful agents in the Earth System, there is growing consensus that socioeconomic behaviour and environmental change are intertwined via feedbacks. For example, avoiding crossing undesired climate tipping points or exploiting natural resources in an unsustainable way requires rapid transformational social change, which may be propelled (intentionally or unintentionally) by triggering change in the Earth System or be triggered by such changes. Thus, rapid shifts in awareness and societal decision-making such as moving away from fossil fuels as primary energy source, will be an integral element of future Earth system evolution.

1.4 Discovery, Diagnosis, Solutions – The Leitmotifs of this Report

This report recommends German Geosciences employ an Earth System Science framework to conduct basic research on the formation and habitability of our planet, responding to today's environmental challenges, and to aid in securing our future livelihoods. Three connected scientific pursuits provide leitmotifs for modern Earth System Science knowledge generation: **discovery**, **diagnosis**, and **solutions**.

Scientific Discovery

Curiosity-driven research will always provide the scientific foundation for understanding the natural world. Many elements of the Geosciences are the source of fascination by both practitioners and amateurs. For example, knowledge of how our planet formed or how and when **life** first developed and diversified into today's biosphere remains incomplete. Studies in these areas will allow us to identify how organisms impact Earth through their metabolism. Observations of atmospheric composition and modelling of extrasolar bodies will provide hints about whether life may exist on planets outside of our solar system and thus whether we are alone in the universe. Furthermore, our ever-advancing observational capabilities reveal how closely deep **Earth processes** are connected to each other and to those at **Earth's surface**. The solid Earth's material properties and energy transfer control plate motion, but at the same time the moving tectonic plates shape the Earth's surface, build mountains and generate earthquakes and volcanic eruptions. Chemical reactions associated with rock weathering are hypothesised to feed back into Earth's climate system through the carbon cycle.

Diagnosis of the State of the Planet

Sedimentary archives and the fossils they contain reveal that Earth's past climate included long periods of stability, as well as significant perturbations to that stability. They preserve vital information about climate system thresholds that were exceeded several times in Earth history to push the system to a new state. Critical questions pertaining to the **modern ocean-atmosphere-cryosphere system** that can be answered by examining Earth's archives include: Where is the excess anthropogenic CO_2 stored in the ocean? How does weather change with climate? How does climate influence habitability, both on land by species change and in the sea by, for example, sea-level rise, ocean acidification, and ocean deoxygenation? Unravelling and then repairing the myriad damages to the Earth System humankind caused in the **Anthropocene** is paramount. Greenhouse gas emissions continue to rise and with it global warming, biodiversity loss persists globally on land and in the ocean, and freshwater overuse and pollution from material waste are climbing, all of which threaten human health, global economies, and Earth's life-support system. To provide a more accurate diagnosis of the state of the planet requires investment in technology, analytical tools, and infrastructure to enhance capabilities for Earth observation, monitoring, and modelling.

Solutions

Tasks for Earth System Science include recommending solutions for mitigating and adapting to climate and global environmental changes and building resilience to **natural hazards**, including earthquakes, volcanic eruptions, landslides, and storms. There is an urgent need for Earth System Science practitioners to design strategies for the exploration and sustainable exploitation of **resources** needed to decarbonise energy production and mobility, and for providing materials for technological products, fertilizer and water. Data must be gathered, long-term monitoring established, and information products generated that will be essential input to, for example, models of future trajectories for the Earth system, local geo-information services, and geotechnical applications. These data and data products will further serve to inform governments and the public about the consequences of global and regional climate change.

1.5 From Earth observation to complex model building

Pursuing the three pillars of modern Earth System Science knowledge generation—discovery, diagnosis, solutions—requires the development and long-term implementation of many tools, methods, and measures that appear in all sections of this report. Below are recommended strategies for their integration and application.

It is critical to detect and monitor change in the Earth System from the global to the local scale to enable discovery, understand the coupling between Earth System components, identify tipping points, and formulate and calibrate predictive models. Predicting the effects of human actions on climate and biodiversity and identifying how close we are to the boundaries and thresholds of humankind's safe operating space, requires development of new sensors and expansion of current Earth observation, monitoring, and modelling networks, all of which will generate vast amounts of data.

Advanced modelling is also a central tool for projecting Earth System trajectories under increasing anthropogenic pressure and for exploring the impact of potential solutions (Fig. 2). A model's accuracy in simulating the real world depends on its ability to incorporate the planet's complexities, the types and amount of data input into the model, and the reliability of the data. 'Big Data' play a key role in increasing model resolution and improving accuracy.

Tools are needed to handle and exploit such vast amounts of data, and high-performance computing infrastructure is required to handle the complex simulations.

The links between observations and models in Earth System Science

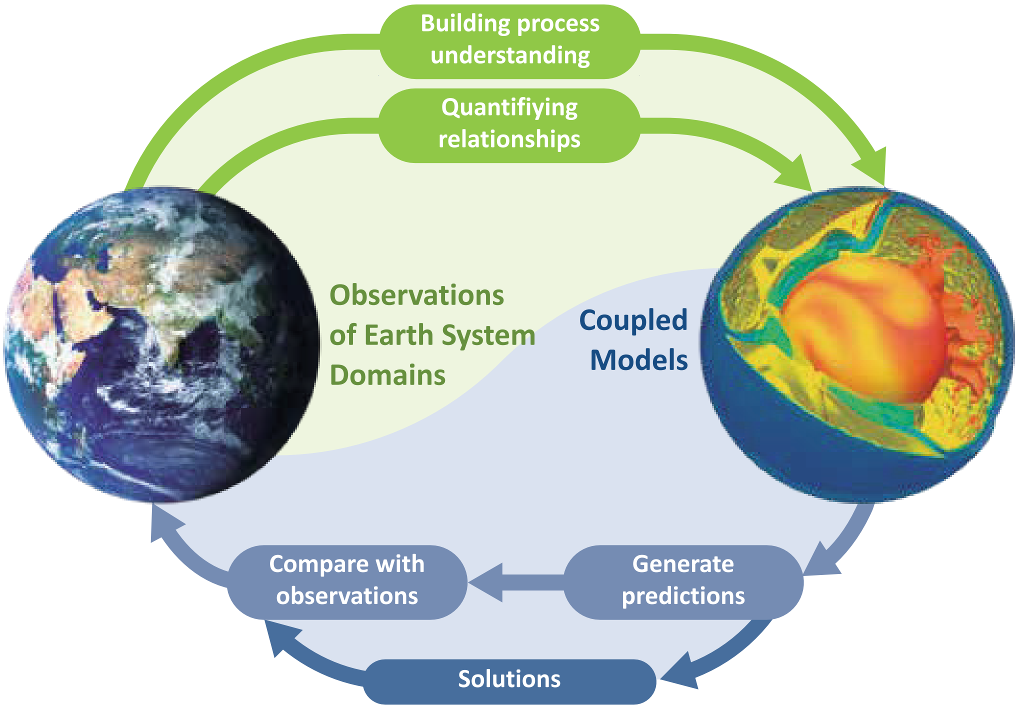


Figure 2. Earth observations are used to derive an understanding of processes and their rates and for quantification of relationships, how observations feed into coupled models, and how observations in turn are used to determine the accuracy of these models and the adequacy and impact of solutions.

1.6 Get young people fit to deal with Earth's future

Education is another activity discussed in this report and pertains to universities and schools. In addition to basic coursework in the full range of fundamental Earth Sciences, the next generation of Earth scientists should be trained in complex system science, the design and operation of advanced observation, analytical and simulation methods, the design and operation of complex software for data and modelling sciences, and how to communicate with the public about the results of their research and options for solutions. This broad education should also include developing closer relationships with social scientists and economists. Course structures that would offer such a broad curriculum and mix of mandatory and voluntary options are not generally available at German universities yet.

1.7 Aims and Structure of this Report

The aims of this report are to (1) initiate discussion and action among the different Geoscience disciplines and their cooperating fields regarding future scientific and organisational development within Germany, and (2) provide stakeholders with recommendations on important actions that are required. Stakeholders in the German science system include: all levels of university administration; politicians in the realm of science, technology, and education; scholarly societies; science academies; research organisations; funding agencies; teachers at schools and universities; and all who are concerned about the role of science in addressing planetary change. Importantly, this report is also directed at our own community, from researchers to deans and university students.

The report is organised into six chapters. Chapter 1 provides the background for the Earth System Science. It proposes the needs in moving forward and summarises approaches recommended to accomplish this transition. Chapter 2 introduces Earth System Science concepts and includes a dictionary of essential terms. Chapter 3 presents seven grand scientific challenges in Earth System Science: (i) deep Earth dynamics; (ii) co-evolution of Earth and life; (iii) the ocean, atmosphere, and cryosphere; (iv) past climate changes; (v) the Anthropocene; (vi) extreme events and risks; and (vii) Earth resources. Chapters 4 and 5 discuss in detail two focus areas for German Geoscience: the application of Big Data to finding solutions to problems and academic education in Earth System Science. Chapter 6 concludes with recommendations for both decision-makers and the scientific community.

A potential risk of embracing Earth System Science is that existing successful disciplines may fear losing their identity or their specialty competence. Creative means and incentives will be needed to ensure synergies among disciplines and to foster cross-disciplinary development of measures to initiate change whilst maintaining specialty competence.

The vision laid out in this report provides opportunities and advantages for the Geosciences, but also poses challenges for universities or networks of research institutions. For example, modern Earth System Science training offers a broader perspective than the traditional disciplines alone, and this increased appeal may lead to growth in the undergraduate population. Improved and expanded research structures, collaboration between research fields, and strong integration of university institutes will strengthen visibility and will enable universities to compete for large research and infrastructure programs. The ultimate goal is to evolve the Geosciences in Germany to meet present and future challenges in research by educating the workforce of the future.

2 The Earth as a System

None of the Earth System's five subsystems—the atmosphere, hydrosphere, biosphere, geosphere, and anthroposphere—can be viewed in isolation. The exchange of energy and matter, as well as feedbacks, among these subsystems maintain Earth System stability over millennia. Some subsystems feature multiple stable states, and a large enough perturbation to one part may shift that system into a new stable state – having exceeded a so-called tipping point. Because Earth's systems are tightly connected, when a tipping point is crossed in one system, it may trigger a cascade of tipping points being exceeded in other systems. With humans as a recent significant perturbing force, several of Earth's systems are now under threat of exceeding their tipping points.

During the 1980s, scientists and policymakers grew to appreciate that Earth is an integrated system of interacting components that included humans. As a seminal NASA report from 1986 put it, "This insight has set the stage for a more complete and unified approach to its study, Earth System Science"[4]. Launched in 1987 and wrapped up in 2015, the International Geosphere-Biosphere Programme (IGBP) led the global community of scientists to understand Earth as a whole. Since then, Earth System Science has developed as the guiding paradigm for the way we view the Earth, allowing assessment of the risks introduced by human activities[5].

Key Elements of Earth System Science

Key elements of Earth System Science are illustrated in Fig. 3. The Earth System features stabilizing mechanisms. These mechanisms are regulations and feedbacks – essentially a complex chain of cause and effect (Fig. 3). Over billions of years Earth's history experienced changes: the feedbacks were overridden – leading to "revolutions" in the way that Earth and life functioned. The Anthropocene, a period in which humans are simultaneously stressing multiple parts of the Earth System in unprecedented ways, will likely be characterised by tipping points as well as chain reactions within ocean-atmosphere and land-atmosphere interactions.

---

[4] NASA (1986).

[5] Steffen et al. (2020).

The Earth system

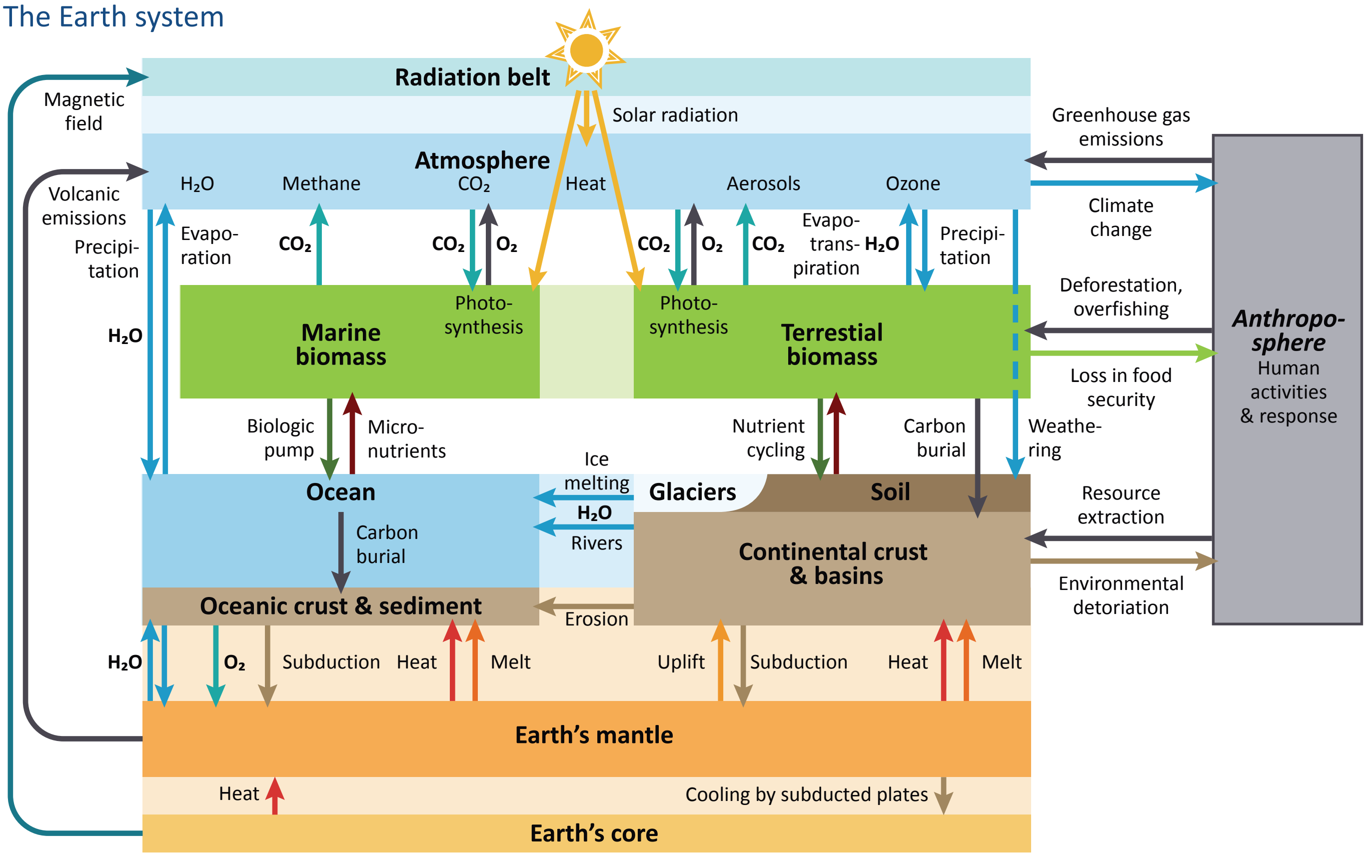


Figure 3. Compartments of the Earth System, forming a series of subsystems that extend from Earth's core to the upper atmosphere and the radiation belt. Arrows indicate the transfer of mass, heat and radiation, or force between compartments. Bi-directional arrows indicate compartments that are interconnected by feedbacks. One-directional arrows indicate forcing external to a compartment, meaning that the properties of the system react to the forcing without affecting the source of the forcing in return. All of the interactions indicated by arrows change through time and thus the subsystems respond when one parameter is changed. The Earth System operates over a huge spectrum of timescales: from billions of years for Earth's mantle to years and less for gases in the atmosphere. Forcing by human activities is shown on the right. Modern system theory suggests that feedbacks with the Earth system affect human behaviour. This interaction is shown here.

This system concept featured in all sections of this report encompasses the Earth's core to the top of the stratosphere and includes life. For billions of years, life on Earth has influenced the composition of atmospheric gases that in turn react with rocks. Some organisms are involved in the formation of new rock, by depositing their skeletons after death.

Subsystem Boundaries

In order to model interactions between Earth's subsystems, we need to define their boundaries (Fig. 4). It is important to define boundaries because what lies outside of the boundary may affect the subsystem but may not necessarily be affected itself – it "forces", or drives change in, the subsystem but does not interact with that subsystem via feedback mechanisms. For example, the top of the atmosphere and its magnetosphere form our planet's outer boundary. Solar irradiation and the convection of Earth's fluid outer core influence the behaviour of this boundary. The sun is outside of the Earth System. It provides our main source of energy and forces Earth's climate but is not affected by what goes on within the Earth System. The location of Earth's inner boundary is less clear. It depends on our perspective, and on timescale. Viewed from

Earth's surface, the inner Earth has its own heat source that drives mantle convection, volcanic activity, and plate tectonics, but in turn is affected by processes that take place at its surface only at timescales exceeding some 100 thousands of years. In contrast, climate models that analyse global change like glacial melting or ocean circulation over decades or centuries exclude the interior Earth. Over this timescale the interior Earth may still force climate in the form of volcanic eruptions that for example eject sulphur dioxide into the upper atmosphere, increasing Earth's albedo. These events present external forcing as over this short timescale the interior Earth is not affected by the climate change that results. The interactions between the interior and the surface of the Earth are most eminent over the timescales at which ocean basins form, continents collide, mountains rise and weather, and material is returned to Earth's mantle. Over this timescale the workings of the inner Earth become an integral part of the climate system and even influence the abundance and distribution of species and their evolution.

Earth system dynamics and system theory – a short thesaurus

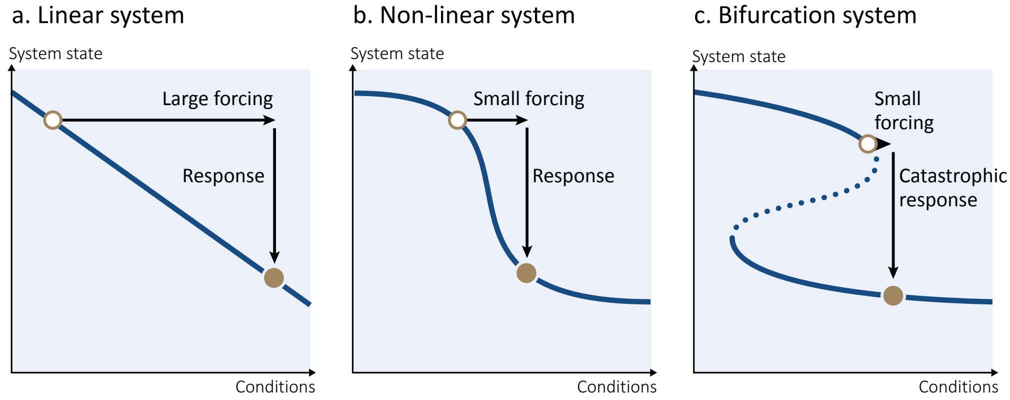


Figure 4. How does the stable state of a system respond to changing boundary conditions (such as a rise in temperature, exertion of force, or an influx of mass)? A system that has been perturbed will always tend to move towards a stable state, shown by the arrows. a) In a linearly responding system, a large forcing leads to a linear response in the system state, where the magnitude is dictated by the coupling coefficient. This response is reversible. b) In a non-linear system, a small forcing can be sufficient to cause strong and even abrupt change in system state (where the steep part of the curve presents a non-catastrophic threshold). c) If a system is close to a "bifurcation point", a tiny change in the condition can result in a large shift to the opposite branch. These bifurcation points are tipping points at which a tiny perturbation can cause a large transition that is irreversible. Early-warning signals tend to arise as systems approach a bifurcation point. Figure after Scheffer et al. (2009).

Socio-ecological Feedbacks

A key concept of the Anthropocene, featured in Section 3.5 of this report, is that human actions affect the Earth System up to planetary scales (Fig. 5). Humans are now an agent "within" the Earth System. Human activities force Earth's subsystems, and humans adjust their behaviour upon recognition of the changes they induced. These types of interactions are termed "socio-ecological feedbacks". The course of action in modern Earth system science suggested in this report is guided by these principles. For developing solutions for society, almost anything we suggest has consequences for other parts of Earth system. For example, mining precious metals to enable "green energy" has severe consequences for local terrestrial and deep-sea ecosystems if not done sustainably, and any suggested solution is doomed to fail if not accepted by society.

As a conclusion from these considerations, conceptualising Earth as a complex system must be at the heart of any strategic Earth Science development.

Earth System Dynamics and System Theory – A Short Dictionary of Terms

System = A "system" is comprised by agents that are connected by fluxes of energy, material and forces that interact by feedback mechanisms. A system has defined boundaries beyond which bidirectional interaction and feedbacks no longer exist, forcing from outside the system without feedback may occur.

Sub-System = Any system can consist of smaller sub-systems in which feedbacks exist internally but also with other subsystems. Sub-system boundaries are flexible and depend on the spatial and temporal scales under consideration.

Forcing = Driver of changes in a dynamical system that affects the system but is not affected by the system. Incoming solar radiation is a perfect example of a climate system forcing. The dynamics of Earth's mantle and its changing convection regime is another example of a climate driver through its role in the growth of continents and provision of marine habitats in shallow continental seas, or repeated formation and erosion of large mountain chains which plays a major role in moderating atmospheric CO_2 content.

Feedback = A process in which changing one quantity changes a second quantity, and the change in the second quantity in turn changes the first. Positive (or reinforcing) feedbacks amplify the change in the first quantity while negative (or balancing) feedbacks attenuate it. Silicate weathering is an example of a negative feedback through its role in regulating the long-term atmospheric CO_2 budget. Rising atmospheric CO_2 leads to warming, intensifying the hydrological cycle, which in turn enhances silicate weathering that withdraws CO_2, leading to cooling.

Critical threshold = A critical threshold that, when exceeded, leads to large and often irreversible changes in the state of the system. For example, a fault ruptures when a small increase in differential stress crosses the strength threshold, triggering an earthquake.

Tipping element = A component of the Earth System that can undergo a qualitative change once a critical threshold in a control variable is crossed, that is, a component that possesses at least one tipping point, like the West Antarctic Ice Sheet or the Amazon rain forest.

Tipping point = A critical threshold beyond which a system reorganizes. Once the tipping point is exceeded, change can be abrupt, or irreversible if positive feedbacks start to dominate, driving the system towards another attractor (e. g., an alternative stable state). One example of a tipping point is permafrost thawing. Above a certain temperature, permafrost will thaw in the Northern Hemisphere releasing CO_2 and methane, which triggers more warming and permafrost loss. The changes to permafrost are irreversible over the same timescale even in a return to initial environmental conditions.

Abrupt change = A change that is significantly faster than the historical rate of change. For example, convection in Earth's core generates Earth's magnetic field, which is relatively stable over thousands of years. At irregular intervals, the magnetic field may become unstable or even rapidly reverses polarity, and the time it takes for it to reverse is comparatively rapid.

Irreversibility = When a change in forcing perturbs the state of a dynamical system, it is defined as irreversible on a given timescale if there is no recovery from this state or if recovery takes substantially longer than the timescale of interest.

Bifurcation = A (saddle node or fold) bifurcation in a dynamical system occurs when a particular parameter in the system, which is observed to be consistently moving in a given direction over a period of time, passes a critical level - at which point a bifurcation, or fork takes place. At this point a stable state loses its stability. If a system is close to a “bifurcation point” a tiny change in the condition can result in a large change into the opposite branch. A bifurcation point can be viewed as one form of a tipping point.

3 The Grand Challenges of Earth System Science

The subsequent sections highlight a selection of some of the issues in which interactions and feedbacks play an eminent role. We place them in a modern Earth Systems Science context.

3.1 Deep Earth Dynamics and its Connection to Earth's Surface

Our ever-increasing observational capabilities reveal how closely deep Earth processes relate to each other, and to those at Earth's surface. The motion of tectonic plates is self-organized by the solid Earth's thermal and mechanical properties, but at the same time induces feedbacks with Earth's surface that have stabilized global climate and geochemical cycles through Earth history. We need novel, fully quantitative Earth models that involve complex system science and that are informed by real-time Earth observations, by deep learning for the analysis of big data sets, by experiments on Earth materials, and by enhanced deciphering of coupled processes in nature and laboratory. These models will form the basis for advanced concepts of hazard assessment and mitigation as well as for a new generation of strategies for resource exploration and their sustainable exploitation.

State of the Science

Only 50 million years ago—a brief time span compared to the 4,570 million years of Earth history—our planet looked quite different. The Atlantic Ocean was narrow, a large ocean separated Africa from Eurasia, the Himalayan-Tibetan system became the largest plateau region and was just beginning to rise, Earth was on average 6° to 8°C warmer than today with no ice at the poles, and different species inhabited our world. We owe the profound changes since then—including the evolution of humans—to the dynamics of Earth's interior, from the core to the moving plates on the surface.

As early as 1915, Alfred Wegener suggested that continents move. But only technological advances, starting during World War II, triggered the 1960s plate tectonic revolution. Sonar systems provided bathymetric data needed to draw detailed seafloor maps, seismologists identified descending plate boundaries through mapping earthquake locations, advances in radiometric dating confirmed the young age of seafloor relative to the old age of the continents, and geophysicists recognized that reversing magnetization in rocks from the ocean floor meant that new oceanic crust is constantly created at mid-ocean ridges and "recycled" by subduction into the mantle at convergent plate boundaries. Courtesy of plate tectonic theory, we now perceive our planet as a dynamic system of moving plates floating on a convecting mantle (Fig. 5).

Observation of dynamic Earth

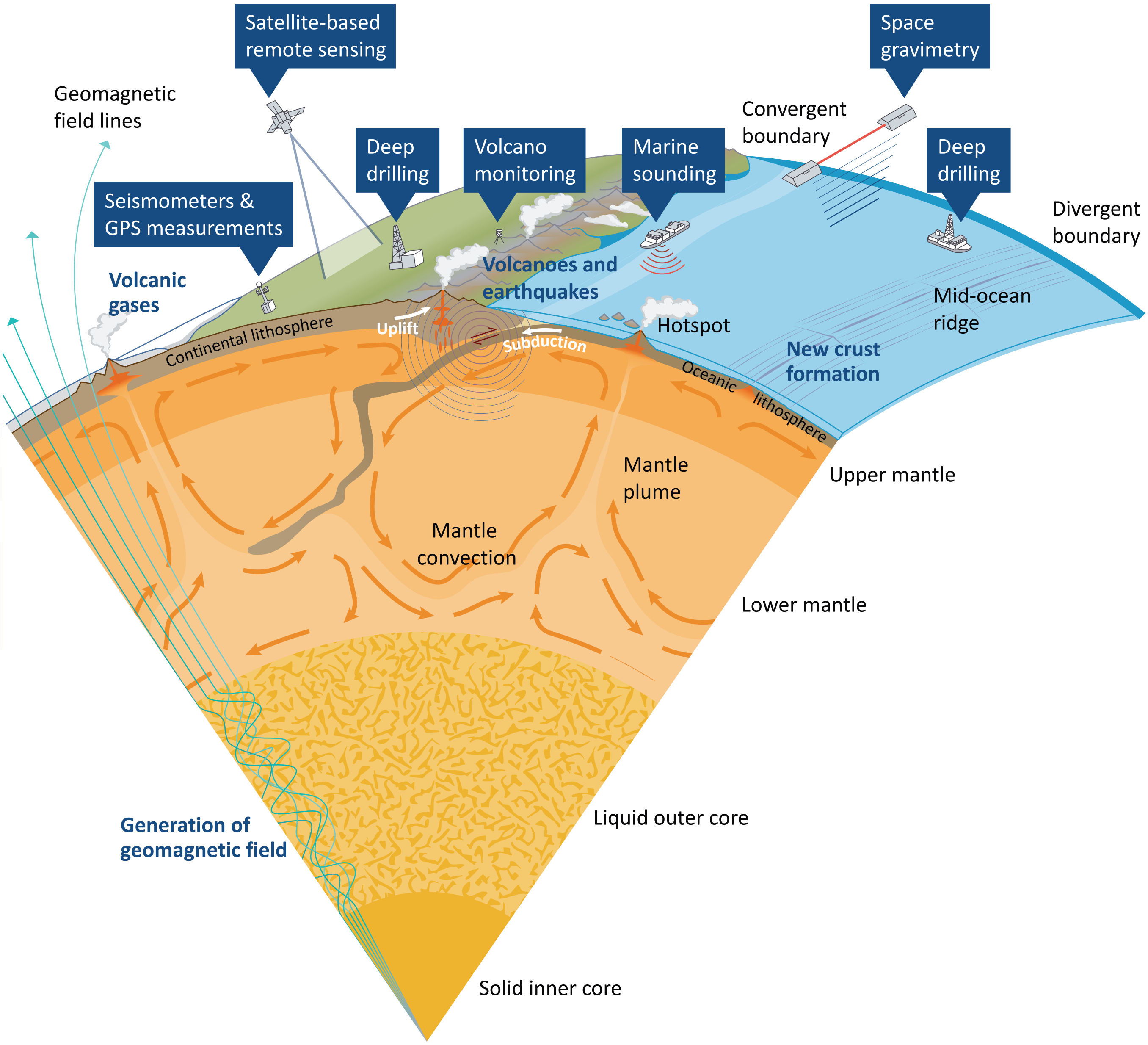


Figure 5. Deep Earth processes, from the convecting outer core that controls Earth's magnetic field to the convecting mantle (lower and upper mantle in orange shades) that drives plate tectonics, shape Earth's surface and influence the evolution of its habitats. Deep Earth processes, such as the subduction of oceanic plates formed at the mid-ocean ridges, drive the growth of continents, the evolution of the atmosphere, and changing surface conditions through geological time. The resulting slow to rapid change at the surface and the responsible processes – such as earthquakes, mountain building, erosion, volcanism, relative sea level change – are directly accessible to ground- and space-based observation technologies. Analysis of the data collected show evidence that multiple feedbacks exist between deep Earth processes, climate, and the changing biosphere. Lithosphere thickness and crustal elevation not to scale.

As technology advances, we are now recording data on the dynamics of the Earth System from the core to the surface in ever increasing resolution, and often in real time. These data allow us to see how Earth's subsystems are connected.

1) Digital monitoring of Earth's surface, interior, and its motion using a range of imaging techniques and geophysical sensors on the ground, in the air, and from space generates quantitative images of the Earth System with extraordinary spatial and temporal resolution.

2) Advanced simulations using powerful computers and codes produce increasingly realistic models of structure and movement of Earth's convecting mantle and core.

3) With radioactive decay-based isotopic and cosmogenic nuclide tools, we determine the "rates and dates" of Earth processes, from the growth of continents to magma formation and ascent, to mountain building and the erosion of the land surface as well as the deposition of sediments.

4) Nanometre-scale mineral analysis and experimental simulation of deep Earth materials are revealing the laws governing the behaviour of Earth materials.

5) Organic and inorganic geochemical isotope proxies have enabled us to reconstruct variations in Earth's past climate and in rock weathering so that we now appreciate how Earth's surface—our habitat—is shaped by the dynamics of Earth's interior and simultaneously acting climate.

The wealth of information enabled by this technology constitutes a milestone for achieving predictive capability in many key areas. We are beginning to see their role in, for example, the improved forecasting of natural hazards, or the reliable prediction of geological resources. Harvesting the fruits of these capabilities to their fullest extent, however, requires the next revolution in Earth dynamics sciences. We need quantitative mechanistic process models to be used as tools for the identification of system interdependencies and thresholds - the crossing of which will push the Earth System to a new state.

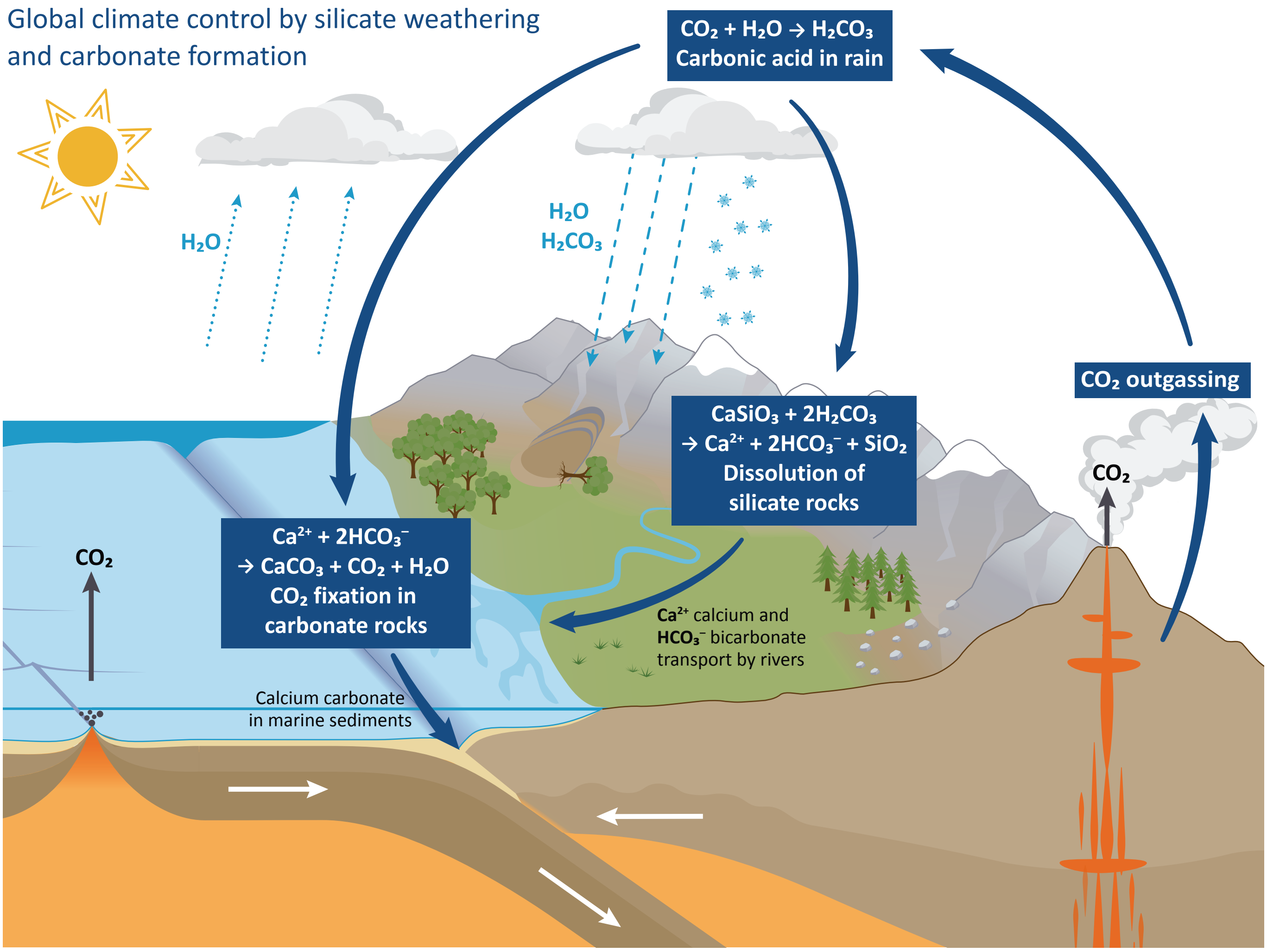


Figure 6. According to the silicate weathering feedback hypothesis, CO_2 emissions from volcanoes are balanced by the reaction of CO_2 with minerals during weathering, followed by burial in carbonate sediments that form in shallow oceans near the continents. The formation of topography by interior Earth forces followed by erosion and weathering thus controls Earth's carbon cycle and the stability of surface temperatures throughout Earth history at timescales of millions of years.

Key questions

Some of the most important questions that need to be answered to better understand how the Earth System operates are:

What drives plate tectonics on a silicate planet?

In our solar system, only Earth currently features plate tectonics, which according to our knowledge of rocky planets is a prerequisite for the evolution of higher forms of life. How, why, and when plate tectonics began to operate on Earth, rather than remain as the stagnant lid style of planetary dynamics displayed on Mars and Venus, is subject of a longstanding debate. How does subduction initiate and what combination of processes is needed to stabilize Earth's current geodynamic style? How do past ice-house and hot-house stages of Earth's surface relate to major changes in plate tectonic activity? It is likely that water controls deep Earth material properties by playing a major role in mechanical and chemical exchanges, which ultimately affects the thermal evolution of the deep Earth. Indeed, water was recently recognized as key in allowing the operation of plate tectonics because of its role in transporting sediments to the deep-sea trenches where they “lubricate” and weaken the plate interfaces. Concerning mantle convection, which is driven partly by the core’s heat loss, two recently discovered long-lived geophysical anomalies at the base of the lower mantle apparently act as nucleation sites for upward mantle flow. However, their origin and composition remain obscure. The subduction and mineralogical modification of hydrated oceanic plates plays a decisive role in moving tectonic plates and subducted ocean water is dissolved in mantle minerals, lowers mantle viscosity, and affects mantle convection. And we still do not know where most of the water is stored: In the ocean or in the mantle?

How unstable are Earth’s deformation processes?

Earthquakes are the most obvious expression of failure of Earth materials. Over the past 20 years, however, satellite-based techniques led to the discovery of so-called “slow earthquakes” that previously went undetected. The new observations showed hours to years of transient acceleration of motion and creep in Earth’s lithosphere. Today, related unstable accelerated slip at plate boundaries can be detected with geodetic and gravimetric methods down to depths of several 100 kilometres. It is hypothesized that changes in rock properties play a role in slow earthquakes, possibly in connection with fluids, but it is just as unclear as the question of the predictability of such slip or their relationship with earthquake rupture. Yet another set of observations shows us that fluids injected into reservoirs in hydrothermal engineering may cause local earthquake swarms, even in regions that are not generally seismically active. Does this mean that the Earth’s crust is close to failure nearly everywhere? All these discoveries challenge our understanding of how Earth’s outermost shell, its lithosphere, responds to stress and often minute changes of its physical state. We need to pinpoint the physical causes of these behaviours and to know how such behaviour impacts the use of the subsurface for technical infrastructure, storage, or resource extraction.

What triggers volcanic eruptions?

Airborne surveys of active volcanoes, geophysical soundings of subsurface magma lenses, and modelling of magmatic processes have revolutionized our understanding of the architecture of magmatic pathways and processes at depths that feed and trigger volcanism. Today we believe that eruptions are governed by a combination of external triggers (such as tides) as well as internal processes and feedbacks in the solid-fluid-gas systems. Magmatic plumbing systems seem to be sensitive to minute changes in magma storage conditions. The challenge is to identify the thresholds in magma storage that will trigger eruptions. We can do that by quantifying the states of individual system components and establishing the way they are coupled to each other and to surface conditions. Using this knowledge, we hope to determine eruption timing, magnitude, and style and whether it is possible to link real-time geophysical signals to magmatic unrest at depth prior to magma ascent and eruption.

What are the deep-Earth-to-surface feedbacks that make our Earth habitable?

Forces deep inside Earth impact surface processes and environments. For example, our planet’s atmosphere may have become oxygenated through redox reactions taking place in Earth’s mantle. Plate tectonic processes can trigger biological evolution by providing new habitats but can also contribute to global extinction events. For example, eruption of massive volumes of basalt that occurred millions of years ago likely cooled global climate, changed ocean water chemistry, and with it the habitability of our planet. The most powerful interaction between moving plates and climate, however, is presented by the hypothesis of the silicate weathering feedback: rising mountains provide reactive land surface through erosion (Fig. 6). Rocks begin to weather. The chemical reactions involved stabilized climate during Earth history by balancing the atmospheric CO_2 emitted by volcanoes and the hot interior of mountain belts. By forming limestone in the ocean, the atmospheric carbon is consumed and locked up in geologic stores for many millions of years. This mechanism has helped to keep the surface temperature of the Earth surprisingly stable over most of its history - but important failures of this feedback during short stages in Earth history led to a "snowball Earth" and a "hot-house Earth". Resolving these feedbacks, their stability, and critical thresholds in the Earth system are essential to evaluate their effects at timescales of thousands to hundreds of thousands of years. Such research may also facilitate the search for life on other planets in our solar system and exoplanets in the nearby universe. Conversely, research on exoplanets will provide insights to better define limits of planetary habitability, which is in many ways a search for a planet with active plate tectonics and weathering feedback.

What is needed?

Several recurring themes are identified in these key questions: many processes interact across virtually all compartments of the Earth System; vastly different processes are coupled across a wide range of timescales and distances; and system state can change from stable to unstable and back rapidly and unexpectedly, and the dynamics of Earth's materials far from equilibrium control these conditions. As with the plate tectonics revolution, we anticipate the next leap in knowledge will come from our ability to decipher the nature, stability, and balance of these interactions. We need to be conscious of, and recognize the critical thresholds involved, and of their scale dependence – both in time and in space from new observations by innovative technologies. Novel strategies for obtaining data will include experiments designed to develop laws of transient behaviour across all scales as a basis for mechanistic models. We need to collect high-resolution time series of observations linking processes viewed at the instrumental time scale (e.g., measured today) to geological archives containing our deep time records (e.g., spanning hundreds to millions of years). To exploit the dramatic increase in high-resolution data we need advance in data science with new technologies such as deep learning. Where observational resolution is limited to unravel mechanisms in sufficient detail, numerical modelling will be instrumental in developing and testing hypotheses, with the goal of filling knowledge gaps and developing improved mechanistic models of Earth dynamics.

Ultimately, the results of this research will lay the foundations for tools and solutions that allow

1) optimizing sustainable storage of waste, matter, and energy as well as the safe exploitation of natural resources;

2) anticipating more reliably the hazards emanating from solid Earth's dynamics such as earthquakes, tsunamis, volcanoes, surface mass movement and more.

Technological development is not all, however. Novel observations must be paired with a growing awareness that processes driving the Earth System processes are virtually all intricately linked and display characteristics of complex systems. Exploiting strategies and methods developed in complex system science will be a key element of future studies of deep Earth, akin to the development that is driving the climate sciences. By taking advantage of these opportunities, we will revolutionize how we view Earth. We will be able to document how the planet evolved in response to geological processes, how deep Earth processes shape Earth's surface, and, importantly, decipher the impacts of human actions on these systems.

3.2 Co-evolution of Earth and Life

Earth's biosphere, atmosphere, and hydrosphere have evolved simultaneously with the solid Earth. Within a hundred million years of Earth's formation 4.54 billion years ago, the ingredients for life were in place: solid rock, water, an atmosphere, and freely available carbon. Yet, we are still grasping for insight into how the first organisms developed and how they diversified into today's vast array of life-forms. Vestiges of early life are recorded in the earliest preserved rocks on Earth in the form of isotope and trace element signatures, molecular biomarkers, and microfossils. Indirect evidence from potential biosignatures from planetary observation and modelling may provide hints that life exists on other planetary bodies and tell us whether we are alone in the universe. A major frontier in Earth System Science is the "deep biosphere" - vast ecosystems living in complete darkness deep below Earth's surface. Today, our growing knowledge of the relationships between the geosphere and organisms is key to finding solutions that will allow Earth to remain within the boundaries of ecosystem stability that supports human life.

State of the Science

The development of the solid Earth along with its hydrosphere and atmosphere is closely linked to the development of life (Fig. 7). Yet the inner forces that continually rework Earth have hidden or erased traces of its birth, its youth, and the origin of the first organisms. Isotopic dating of meteorites indicates that the solar system formed 4,568 million years ago, with Earth possibly forming only 30 million years later. The moon-forming impact (Gaia/Theia, 4,530 million years ago) resulted in a deep magma ocean in Earth's interior from which the atmosphere and the ocean degassed as the interior crystallized. Cooling and at least partial stabilization of an early crust occurred rapidly. Water appears to have been present by around 4,400 million years ago, based on zircon oxygen isotope data. Two hundred million years after solar system formation, the solid Earth, the moon, the ocean, a proto-atmosphere, and the nuclei of the first continents were in place, providing the physical and chemical ingredients for life.

The oxidation level of Earth's interior rose rapidly after its metallic iron core separated, which was essential for the development of a carbon dioxide-rich and hydrogen-poor atmosphere by volcanic outgassing. Life may have begun 4,000 million years ago, during or possibly even before the so-called "Late Heavy Bombardment" of Earth by impactors 3.8 million years ago. Earliest evidence for life lies in isotope and trace element signatures in the oldest preserved sedimentary rocks. Microbial sedimentary structures called stromatolites and similarly aged organic remains that may represent the oldest procaryotic microfossils are the first direct and unambiguous indication for the existence of life by ~3,500 million years ago.

The environments in which life developed were strongly influenced by solar irradiation, the style of early plate tectonics that shaped Earth's surface, as well as the physical and chemical conditions for exchange reactions between water and minerals in rocks. These ingredients were restricted to specific environmental niches. Photosynthetic microbes were probably active for over a billion years before the liberation of free oxygen gas to the atmosphere finally outstripped its removal from the ocean and into oxidized iron deposits. This led to the "Great Oxidation Event" ca. 2,450 million years ago when atmospheric oxygen started to accumulate. Another big leap in the co-evolution of atmospheric chemistry and life occurred 540 million years ago during the so-called "Cambrian explosion" when all fundamental assemblages of animal species rapidly appeared in the geologic record. The rise of animals may have been triggered by enhanced seawater oxygenation that in turn may have been engineered by evolutionary change amongst carbon-fixing organisms. The rise of oxygen also influenced the mineralogy and geochemistry of Earth's surface. In fact, more than 95% of all oxygen ever produced through photosynthesis is today locked up in sediments and rocks. If subducted into Earth's mantle oxygen may alter its physical properties.

Co-evolution of life and Earth's subsystems

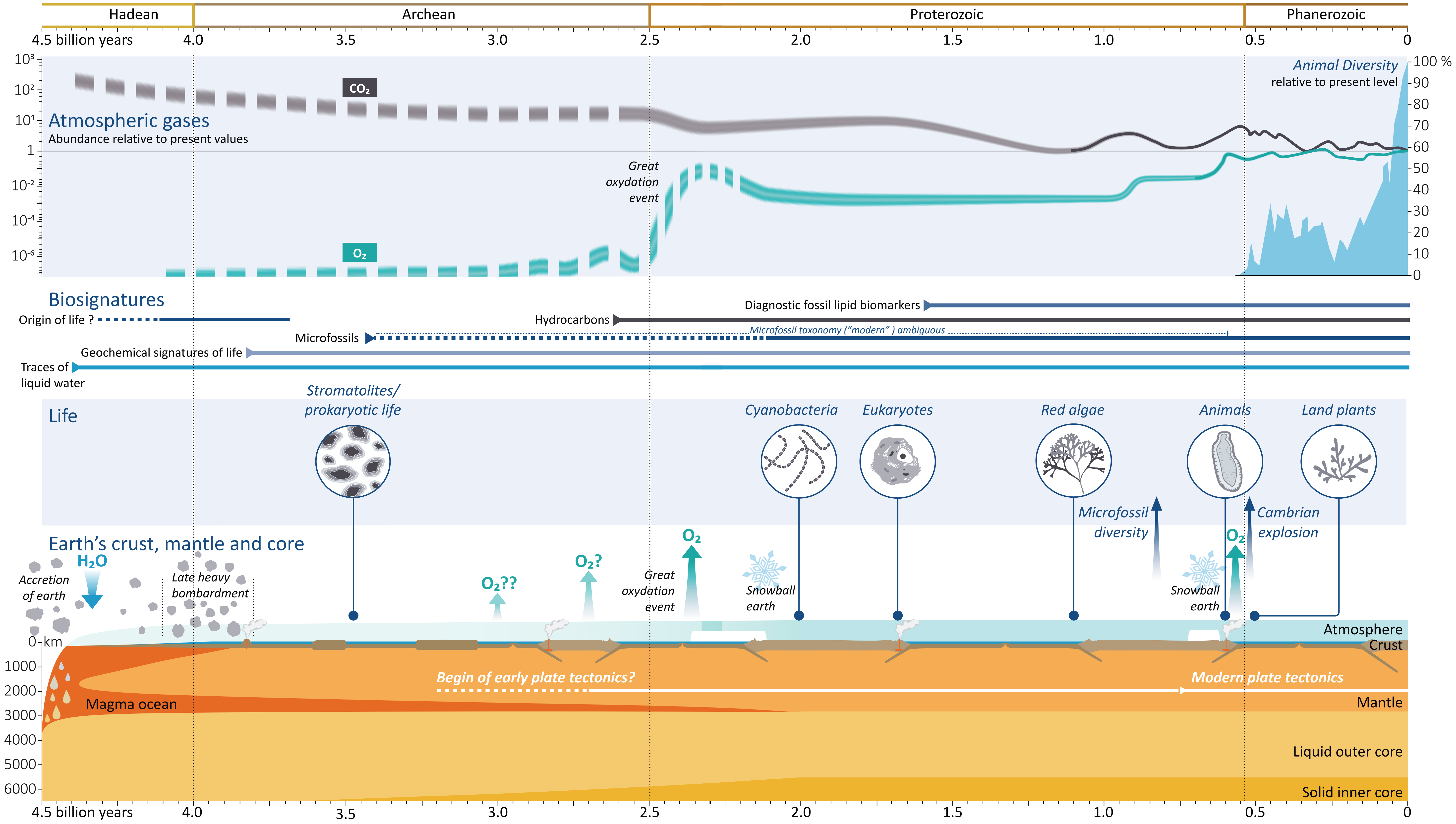


Figure 7. Life and the solid Earth have co-evolved in all Earth's subsystems: The physical state of Earth's mantle (lower panel) is linked to the dynamics of its surface and life evolution through plate tectonics and was instrumental in setting and controlling the composition of Earth's atmosphere through time (upper panel). Organisms produced photosynthetic oxygen and thereby converted atmospheric CO_2 into organic matter, which became buried in sediment. Life thus stabilised atmospheric temperature together with the silicate weathering feedback, which in turn was driven by plate tectonics and mountain building. Shown are also new biosignatures that allow reconstruct the evolution and diversification of organisms on Earth and, possibly, on other planetary bodies. Figure after Raup & Sepkoski (1982), Lyons et al. (2014), Catling & Zahnle (2020), Hallmann, GFZ, (pers. comm.).

Without life, Earth would look very different. Its atmosphere would be oxygen-free. Without plant transpiration, the water cycle would be completely different, affecting climate and continental erosion. Plant roots stabilise soil against erosion, leading to landforms that differ greatly from abiotic equivalents. Terrestrial and marine life is part of a massive "organic" carbon cycle through which 150 billion tons of carbon are exchanged annually between the atmosphere, terrestrial plants, and marine biota. However, even the "geologic" carbon cycle, which stabilises Earth's climate by balancing volcanic emissions via weathering of silicate minerals ultimately finds a biologic sink in marine carbonate sediment. Photosynthetic oxygen is being subducted into the Earth's mantle by plate tectonic processes where it affects the physical conditions of the deep mantle and its dynamics. On the other hand, plate tectonics strongly moderates and even drives biological evolution, causing ever-changing surface conditions and environments throughout Earth's history.

Key questions

Although Earth scientists have long realized the importance of the closely interwoven co-evolution of the deep Earth and life, we are not even close to deriving the details and complexities of these connections, their mutual dependencies, and their history during Earth's evolution. The most important questions are as follows.

Where and how did life first evolve?

The young Earth's surface environments and geochemical cycles would have been very different from those of today. Life may have emerged in hydrothermal systems prior to the Late Heavy Bombardment, some 4,000 million years ago, as indirectly suggested by molecular clock analyses and by extrapolating genetic information from extant biota towards ancestral proteins. The prebiotic organic synthesis pathways that provided the building blocks for life are poorly understood. The "Panspermia" hypothesis, positing that comets and meteorites served as vehicles to transport life from other cosmic sites to Earth, is highly debated. Nevertheless, such extra-terrestrial materials are known to contain diverse biology-like nucleobases and 'left-handed' amino acids. The exact process of how chemical reactions transited into a self-replicating cellular system may be considered the holy grail of biology and the Earth sciences. The Hadean rocks that may have witnessed biogenesis, but that no longer exist on Earth, are still present on Mars, whose surface saw liquid water back then and whose tectonic system shut down around 4,000 million years ago. If the emergence of life—with or without meteoritic input—was not restricted to Earth, Mars may hold the clue to how life started, highlighting the exceptional relevance of exploring fossil, possibly biological organic matter beyond our own planet.

Are we alone in the universe?

The discovery of approximately 4,900 exoplanets (as of December 2021) indicates the possibility that life exists elsewhere in the galaxy. Searching for evidence of extra-terrestrial life will continue during the coming decades. A common assumption is that a habitable planet must be Earth-like: not too hot and not too cold, such that liquid water persists. This narrow temperature window exists within a certain distance from the mother star, and on a planet that, like Earth, is equipped with a silicate weathering thermostat that that stabilises atmospheric temperature. Astrobiologists search for "habitability": the optimal planetary size, distance to star, and planetary interior, and for "indirect bio-signatures" such as atmospheric chemistry. Closer to home, in our solar system, life can be searched for in situ. Targets are Mars as well as the icy moons of Jupiter and Saturn. On Europa, a thick water ice crust covers what is presumed to be liquid water, whereas some of the methane of Enceladus geysers could be produced by methanogenic archaea. Direct biomarkers employed in the search include the likelihood of liquid water, organic molecules, molecular biological tools, metal isotopes, and gas geochemistry, measured *in situ* or by return missions.

What stabilizes Earth surface conditions for life to develop?

Solar radiation in Earth's early history was a mere 70% of what it is today. Surprisingly, the surface temperature of our planet has remained within limited bounds not far from the present, always yielding temperature conditions that allow water to exist at Earth's surface and that are conducive for the evolution of organic life based on proteins. This contrasts with the other silicate planets that exist in Sun's habitable zone, Venus and Mars, both of which took opposite paths. On the early Earth, a biologically maintained methane greenhouse was likely responsible for preventing Earth from entering a runaway glaciation. Today, the silicate weathering cycle is the key process. Because water never fully evaporated, it was protected from loss from the atmosphere by photolysis to space.

Nevertheless, despite the overall steadiness of the Earth system, repeated large-scale destabilisation has occurred in the past, leading for example to long-lasting and global glaciation (e.g., the 'Snowball Earth' stages in the Late Proterozoic). How exactly the associated processes and their rates are coupled, how such destabilisation and re-stabilisation of Earth's surface conditions from global glaciations or the Cretaceous 'hothouse' stages has occurred, how this affected life and was affected by life, and how the return to the more stable range of conditions of recent Earth history was powered, remains enigmatic and one of the least understood questions of the co-evolution of the Earth-life system.

How did life diversify?

The principle of gradual change of characters is one of the major concepts of evolutionary theory and allows the reconstruction of phylogenetic trees based on genetic and morphological traits. These trees, however, do not inform the absolute time intervals between branch points. Determining the timing requires correlating branching knots with the occurrence of certain fossils of known absolute age. The complementary concept of „molecular clocks" derives time information from sequence distances of biological macromolecules. To fully exploit the potential of the vast amount of genomic data available from geological archives, molecular clocks will benefit from enhanced calibration against geological clocks employing macro-, micro- and molecular fossils. Recent advances in fossil lipid research will provide an increasingly 'readable' record. By enhancing our understanding of the timing, locale, and conditions surrounding or determining such evolutionary step-changes, we may eventually understand the underlying drivers for increasingly complex life.

What key roles do biota play in today's Earth?

Life itself amplifies and dampens fluxes of materials and energy on Earth and redistributes elements by, for example, forming rocks composed of carbonates such as limestones or that are rich in organic carbon. We need to understand these feedbacks, as they are so critical to safeguarding the boundaries that define a safe operating space for humanity. Novel current and future questions are: 1) What role does the deep biosphere play in the Earth system? This poorly known subterranean habitat, which includes the deep seafloor and Earth's terrestrial "critical zone" (Fig. 8) offer organic carbon, nutrients, and redox partners, and thus provide the compositional and physical conditions for life. Microbial life in these zones, in turn, strongly alters these zones by extracting nutrients and water and returning carbon to the atmosphere. 2) How do biota influence landscape form and evolution? Plants and burrowing and herbivorous animals catalyse the way climate is transmitted into landscapes. Developing bio-physical laws and parameters that describe these processes will give us the capability to predict how such bio-geo interactions modify landforms, how restricting sediment transport to the ocean will alter coastal landscapes and delivery of nutrients to marine ecosystems, and how global changes will impact the services landscapes provide to humankind. 3) Life is an essential agent in soil formation in the critical zone between rocks and atmosphere. How do microbial, biochemical, and physical processes in soils function, what are the rates of such processes, and what is their response to changing climates?

Geo-bio interaction in the critical zone

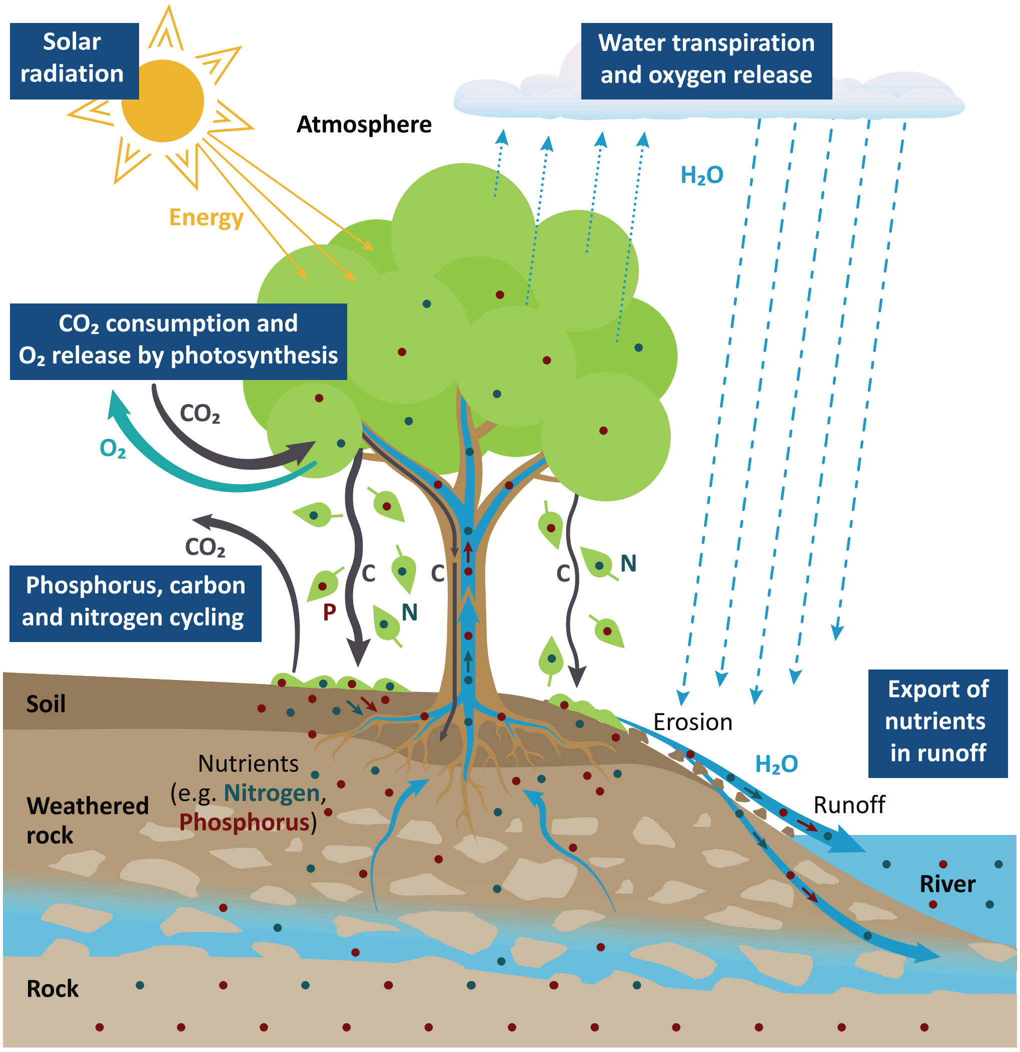


Figure 8. The interactions between life and Earth's subsystems are fundamental to stabilising surface conditions and maintaining Earth's habitability. Shown here is an example of the land surface called the Earth's "critical zone". Here, plants extract nutrients from rocks and recycle them into soil for re-use and use photosynthesis to convert atmospheric CO_2 into free oxygen and organic matter. Terrestrial plants are a key player in regulating Earth's water cycle through consumption and evapotranspiration. Microbes play a key role in all soil processes. Figure after Uhlig & von Blanckenburg (2019).

4) How will global change affect marine biodiversity and ecosystem functioning? Ocean acidification, ocean warming, nutrification, and deoxygenation all impact marine primary productivity and marine food webs and microbial diversity. These long-term perturbations to the marine environment will potentially amplify effects that, in the coming decades, will have important implications for biodiversity, food supplies, and the uptake of excess atmospheric CO_2.

What is Needed?

These examples highlight the exceptional interconnectivity between the various biological and geological components of our planet, which must be studied as an integrated system. But also exploring how anthropogenic activity affects this delicate balance between the Earth and the functioning and diversity of life on Earth will provide ample new avenues for discoveries that cross the traditional disciplinary boundaries and highlight the need for synergistic integration of disciplines.

Such integration requires approaches that effectively use the massive data sets emerging from remote sensing and molecular biological and genetic tools. Fully exploring the deep Earth-biosphere interconnection requires constraining the geochemical exchange between Earth's interior, and the surface and atmosphere—both today and through time—and determining its impact on climate and the availability of biologically important elements. Exploring how life in the deep biosphere thrives requires both terrestrial and marine drilling campaigns suited to perform sensitive molecular biologic (including omics) analytics jointly with nano-scale mineralogical and geochemical surveys including inorganic and organic molecular and isotope proxies, as well as development of reactive transport models that simulate microbial dynamics.

Understanding how plate tectonic processes shaped early Earth environments that allowed prebiotic chemical synthesis is essential. So is exploring catalysis at mineral surfaces and the geochemistry of early hydrothermal systems. For constraining biological diversification, correlating phylogenetic branching points with the occurrence of certain morphological and molecular fossils of known absolute age is a paramount task. To search for evidence of early life on Earth we need to advance geochronological tools and molecular clock analyses, establish the geomicrobiology of extreme environments, and further develop geochemical fingerprints such as inorganic and organic chemical biomarkers and metal stable isotope fractionation that are sensitive to metabolism.

The search for life elsewhere in the solar system will eventually involve the targeted return of extra-terrestrial materials whose minute traces and biological diagnostics are exceptionally vulnerable to contamination. These approaches will benefit from the lessons learned while studying Earth's oldest hydrocarbons.

3.3 Present and Future of the Ocean, Atmosphere, and Cryosphere

The closely coupled atmosphere-ocean-cryosphere subsystem plays a central role in Earth system dynamics. It regulates Earth surface temperature, fresh water availability on land, and the atmosphere-ocean carbon cycle. In addition to exercising major control over many functions to enable a habitable planet, this subsystem plays a critical role in maintaining a sustainable food supply. The potential for surprises and sudden changes in the climate demands establishing a comprehensive set of Earth observing capacities and fully coupled Earth System models that represent all of Earth's subsystems including the human domain. Operating in combination, these efforts shall enable the assessment of future opportunities for and risks to humanity.

State of the Science

Earth's atmosphere, ocean, and cryosphere are a closely linked subsystem that exerts fundamental control over and provides essential functions to the Earth System. Each is very sensitive to external forcings, and they are coupled to other parts of the Earth System via complex feedbacks. Decades of scientific research have illuminated the intricate interplay of these three subsystems, how they have controlled and responded to changing climates throughout Earth history, and how these subsystems will evolve.

The **atmosphere** plays a central role in setting Earth's surface heat balance. Due to the partial opacity of the atmosphere in the mid-infrared spectral band, it heats Earth's surface by about 33°C compared to a hypothetical planet with the same albedo but no atmosphere. This function provided by the atmosphere and its content of water vapor, methane and carbon dioxide is the Earth's natural greenhouse effect that makes Earth habitable. However, the atmosphere also increases Earth's albedo due to cloud and haze formation, which substantially modifies Earth's energy balance. Atmospheric transport of heat and moisture directly impacts the marine and terrestrial biosphere, as it determines the mean climate and seasonal cycles, but also influences extreme events such as floods and droughts, heatwaves, and cold spells, as well as hurricanes and the shift or lack of monsoon systems.

The **ocean** plays a critical role in moderating global climate and climate change. The ocean limits the anthropogenic temperature increase in the atmosphere through the uptake of more than 90 percent of the heat generated by the enhanced greenhouse effect resulting from the emission of CO_2, CH_4, and other substances. The ocean also absorbs up to today ca. ¼ to ⅓ of the carbon dioxide that has been released from the burning of fossil fuels. The ocean is a critical pacemaker for climate variability on many temporal and spatial scales, including decade-long mega-droughts, century-long cold spells, and glacial-interglacial cycles at millennial time scales. The ocean hosts the largest connected biosphere on the planet with an only partly discovered biodiversity. Over evolutionary timescales, the marine biosphere interacts with the land-based biosphere and is influenced by the geological processes of plate motions driving changes in habitat. Today, the marine biosphere plays an important role in food security for coastal communities and in biologically mediated cycles of carbon and nutrients. In particular, the deep ocean remains one of the last frontiers of discovery on our planet.

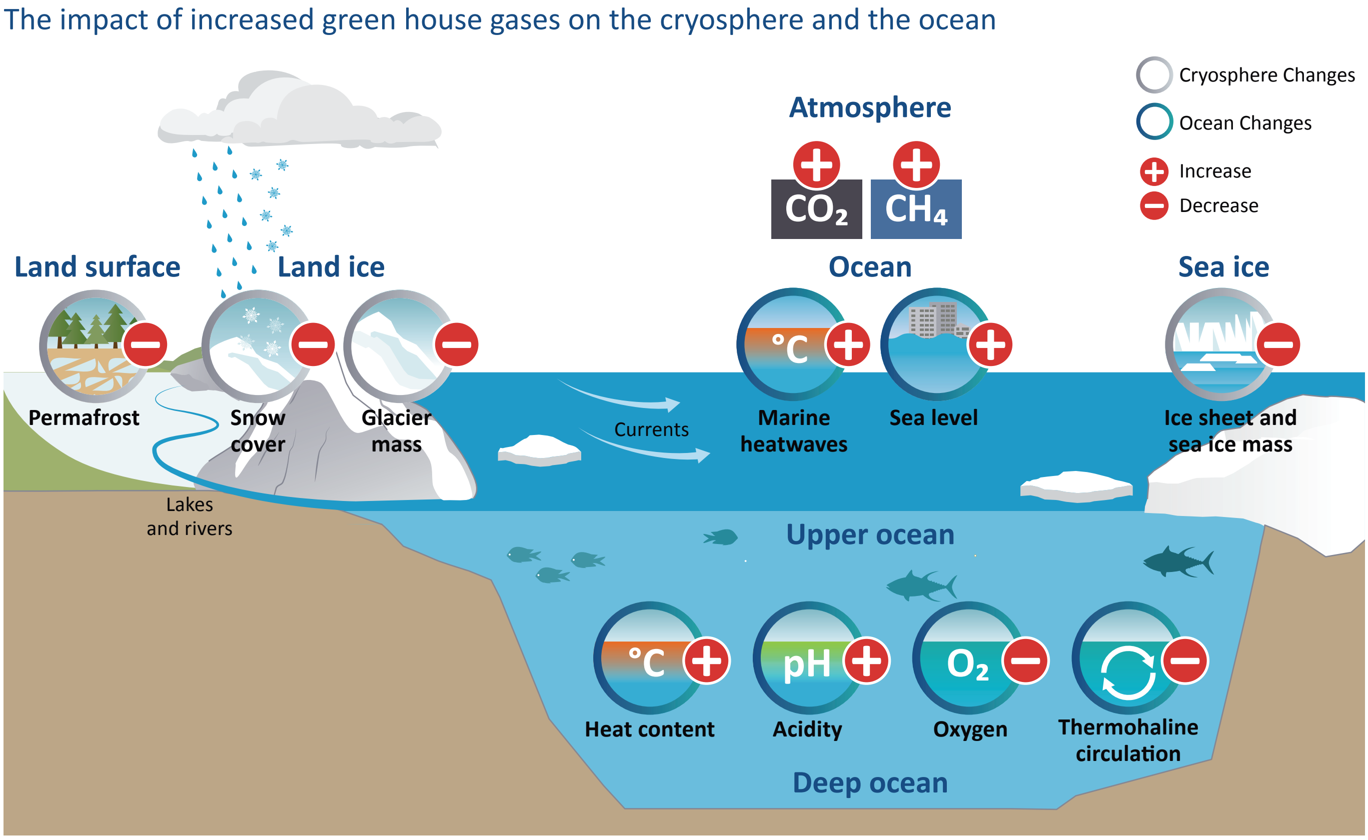


Figure 9. Schematic view of the changing ocean-cryosphere subsystem and its response to changes in greenhouse gas concentrations in the atmosphere. Figure after IPCC (2019).

At present, the largest components of the **cryosphere**, the two polar ice sheets, Greenland and Antarctica, together lock up an equivalent of approximately 120 m of global sea level, of which up to 7 m could be released in as few as 200 years due to unabated anthropogenic warming. Terrestrial glaciers moderate the annual delivery of water resources for at least 1 billion people, a service that is under increasing threat as the glaciers rapidly retreat. In addition, the cryosphere influences Earth's surface heat balance through the self-reinforcing ice-albedo feedback that is particularly strong at high latitudes (Fig. 9).

Today, this system has responded to anthropogenic greenhouse gas emissions and the ensuing global warming, as well as other large-scale human-induced changes such as land use and the introduction of a variety of pollutants in all ecosystems, that has been measured and documented worldwide. This coupled system is drifting towards a new state with largely unknown regional and global impacts, changes in the availability of fundamental resources such as fresh water and disruptions of ecosystem health and thereby the many benefits that the natural environment provides to humankind. In short, these far-reaching changes to the ocean, atmosphere, and cryosphere threaten the habitability of our planet for advanced human civilizations.

As the atmosphere and ocean have warmed, the snow-covered area and the ice volume have diminished. Climate change has led to increasing atmospheric temperatures and ocean heat content, sea level rise, ocean heatwaves, coral bleaching, and dramatic increase in melting of ocean-terminating glaciers and ice sheets around Greenland and Antarctica. More indirect impacts of climate change are growing oxygen minimum zones in the ocean, and there is an expectation that the global ocean overturning circulation will slow down in the future. While global warming is expected to generally accelerate the water cycle, precipitation may become less frequent and decrease in quantity in many regions, while in other regions it increases. Changes in either direction represent significant adaptation challenges for local and regional communities. With the changing climate, we also expect changes in weather, including increased frequency of extreme events such as storms, heatwaves, floods, and droughts. Societies need to know how the frequency and strengths of these events will evolve under climate change, how their forecasts can be improved, and what specific adaptation measures and solutions arise from these predictions.

Key questions

Earth System Science can provide prognoses for future climate scenarios, including slow onset and extreme events, as well as determine how close parts of the climate system are to tipping points. To provide this knowledge, Earth System Science uses 1) rock and sediment archives of the geological past, 2) a wide array of land, ocean, and atmosphere observational data at increasingly high resolution, and 3) advanced Earth System models. Together, this Earth System Science tool kit provides fundamental data that can be used to develop and improve climate change adaptation and mitigation measures and guide policy, governance, and infrastructure development decisions. In this context, some of the most pressing questions are:

How do atmospheric trace gases and aerosols impact climate?

Despite their exceedingly low fraction (~ 0.0001%) of the atmosphere's total mass, many trace constituents decisively influence the atmosphere's behavior. For instance, ozone and free radicals (such as the hydroxyl radical, OH) govern many processes in the atmosphere, including its oxidative capacity, and thus the rate at which other gases such as methane, hydrocarbons, or nitrogen oxides are removed from the atmosphere. Life on Earth is extremely sensitive to certain atmospheric constituents, including ozone, nitrogen oxides, and particles occurring at concentrations of several to several ten parts per trillion near the surface. In urban centers, they (and many other noxious species) are found at elevated levels. It is estimated that on a global scale the combined effect of ambient air pollutants leads to an excess mortality of 9 million individuals per year.[6] A further class of atmospheric constituents are aerosols. Aerosols frequently dominate the radiative properties of the atmosphere, either directly by absorbing (e.g., black carbon aerosol) or reflecting (e.g. sulfate aerosol) radiation, or indirectly by influencing the formation of fog and clouds. Furthermore, aerosols can be hazardous to human health. To resolve how trace gases and aerosols impact climate, we need to develop the ability to quantify the atmosphere's capacity for self-cleaning and to quantify air quality with respect to gases and aerosols. In particular, we need to investigate the role of aerosol and cloud microphysical processes (including ice multiplication), convection, and the properties of cirrus clouds needs to be studied.

A further key challenge is to decipher the role of increasing amounts of water vapor in the energy budget, how it affects atmospheric dynamics, and its effect on stratosphere-troposphere interactions. Today, the full spectrum of analytical techniques, including chemical ionization mass spectroscopy and optical spectroscopy, is applied to studying atmospheric gas and particle composition. In particular, optical spectroscopy can be used both in the laboratory to collect in situ measurements and on satellites to remotely

---

[6] Fuller et al. (2022).

sense atmospheric composition. Remote sensing techniques like multi-axis differential optical absorption spectroscopy (MAX-DOAS) or Light Detection and Ranging (LiDAR) allow scientists to routinely probe the atmosphere in three dimensions. Moreover, satellite-based sensors provide daily global maps of a whole set of atmospheric trace gases at kilometer resolution.

In addition to collecting and analysing observations, atmospheric dynamics are explored by ever more refined models that take into account the fluid dynamics of atmospheric flow, phase change of water, radiative processes including 'short wave' (i. e., wavelength below 3 µm) incoming radiation and 'long wave' outgoing radiation, processes leading to precipitation (rain, snow, hailstorms), and atmosphere-surface exchange processes (e. g., dry deposition of aerosol and gases). The combination of observation and modelling has enabled the projection of possible futures during anthropogenic climate change. Today, climate models allow a much more robust projection of global average climate change as well as regional changes of many parameters, such as temperature, precipitation, and insolation, and their seasonal and longer-term evolution. An evolving modelling application is the ability to provide a more robust attribution of singular events to climate change based on sound probabilistic analyses. In addition, models have become an important economic tool because they enable disaster risk reduction, mitigation, and avoidance.

How does the uptake of greenhouse gases by the ocean and other climate-related changes affect ocean biological and chemical cycles?

Since the Industrial Revolution, increases in downwelling longwave radiation resulting from excess greenhouse gas concentrations in the atmosphere have led to warming of the ocean. A significiant increase in the upper ocean heat content over the past several decades has been observed and was also detected in the ocean's deepest layers. Seawater expands as the ocean warms, contributing to sea level rise. In recent years, melting of land-based glaciers and the two polar ice sheets have contributed to the near doubling of the observed sea level rise - currently more than 3cm per decade. Since 1982, global warming has also led a doubling in the frequency of marine heatwaves, which have also increased in intensity. A warming ocean has led to (a) an increase in tropical cyclone wind intensity and rainfall, (b) an increase in extreme heat waves, and (c) in combination with relative sea level rise, to stronger coastal inundation and erosion, affecting billions of people who live along the coast and on the many low-lying Pacific islands.

Higher levels of CO_2 in the atmosphere directly lead to increasing levels of dissolved CO_2 in the upper ocean, lowering the ocean's pH in a process known as ocean acidification. It is estimated that the ocean absorbs about 30% of the excess CO_2 emitted to the atmosphere from fossil fuel burning. Moreover, surface warming combined with an increased upper ocean stratification has resulted in a 2% reduction of the dissolved oxygen in the ocean over the last 50 years.

As a result of the many ocean changes, some marine species have shifted their geographical ranges and seasonal activities, typically towards the poles. Altered interactions between species have cascading impacts on food webs and ecosystem structure and functioning. For many marine ecosystems, the combined stresses of climate change, habitat overuse and destruction, and pollution have led to dramatic shifts in ecosystem composition and health that are not yet well documented or understood. To secure ocean ecosystem services for future generations requires taking decisive action on climate change. A paramount task is to resolve how biogeochemical cycles – in particular in the carbon cycle – interact with climate system components and how they are linked to land and ocean carbon sinks, atmospheric composition, and climate change.

How much more excess atmospheric CO_2 can be absorbed by the ocean in the future and whether the meridional overturning circulation will slow down and eventually stop remain poorly understood. This includes the role that biological CO_2 drawdown plays, that equally remains unclear due to a number of competing processes. The coupling of ocean models with more complete biogeochemical models is improving investigations of the complex interactions of the ocean-climate system on interannual to millennial timescales.

What is the amount of potential ice loss through the most vulnerable ice streams in Greenland and Antarctica?

Although glacier bodies around the world are inherently local and heterogenous, new data permit global quantification of mass and its changes over the past few decades. A prerequisite to this quantification was the advent of satellite observations beginning in the late 1970s. A global overview of the state and changes of the cryosphere has emerged. Satellite altimetry has enabled the tracking of elevation changes on the Greenland and Antarctic ice sheets, showing seasonal changes, year-to-year fluctuations, and multi-year trends that could be attributed to larger-scale global changes. Laser interferometry now provides information on the movement of ice sheets at kilometer scale. The development of gravitational remote sensing techniques represented a breakthrough that permitted tracking of ice sheet mass changes with unprecedented precision and seasonal resolution. These data were essential for calculating the amount of sea level rise that would be expected if the ice sheets melted. Key input to these calculations are observations gathered by several means at the interface where ocean currents interact with the grounding line of terminating ice streams. Combining this modern information with reconstructions based on paleoclimatic records, it has become clear that the ice sheets sustained large, irreversible changes in the climatic past of our planet and, therefore, such rapid changes are possible also in the future. In addition, these observations provide the basis for a better, more detailed understanding of polar oceanography. High-latitude water masses are defining deep ocean properties and thus have a long-term effect on the global circulation and water mass distribution.

With kilometer-scale resolution now available, simulations are capable of realistically resolving ice stream dynamics. While this has substantially increased our ability to locate dynamic hotspots on the ice sheets, it has also highlighted the need for more detailed observational information of bed topography and better knowledge of the physics at the ice sheet-bed interface. The next challenge is to couple ice sheet models to dynamical high-resolution ocean models to accurately represent under-ice shelf processes.

What is needed?

Three elements of a more robust approach are proposed below.

We need an advanced "Earth **Observing** System" that integrates real-time data on the atmosphere/ocean/cryosphere systems. It would supplement the space-based ocean observations with a global in situ observing system that is taking advantage of the increasingly autonomous robotic platforms such as profiling floats and gliders to supplement the high precision measurements from research vessels covering the full depth range of the entire world ocean. This observing system would be capable of using deep learning techniques in the analysis of the resulting big observational data sets. Such an observing system would allow us to establish the databases required for understanding Earth System processes, for assessing past and present states of the systems, and for developing future scenarios.

Furthermore, Earth System observational data are incorporated into models to improve our ability to decipher the dynamics of coupled processes in nature. **Models** of the atmosphere, ocean, and cryosphere in stand-alone and coupled versions have advanced rapidly over the past decades. However, in order to exploit the full potential of these models, they have to be integrated into fully coupled Earth System models that represent all subsystems, including the human domain. Their design and architecture take advantage of conceptual, statistical, and innovative numerical approaches including "digital twin" frameworks, further discussed below (see section 4.4 "Data Science"). Earth System modelling will also require a quantum leap in the representation of physical processes such as cloud formation in the atmosphere, ocean weather including extremes, or dynamic and thermodynamic processes at the ice sheet-ocean interface. It also requires a quantum leap in resolution of these comprehensive models, with a computational demand that exceeds the capacity of current modelling centres by orders of magnitude. The understanding of potential surprises in the climate system demands a combined monitoring and modelling effort in Earth System Science.

Observations, models, and the new concept of "digital twins" of the Earth play a major role in exploring **options for solutions** to problems caused by the increasing pressure on the Earth system by human activities. Such options for interventions are urgently needed and require a healthy balance between basic- and applied research. Examples of options for solutions of critical problems include: 1) projections of regional and local relative sea level rise in the next 50-100 years, including all Earth System processes; 2) planned protection, retreat and relocation options for inhabited areas and infrastructure and providing information on adaptation measures including dikes, sand bars; 3) nature-based solutions for CO_2 removal from the atmosphere; 4) predictive skills of seasonal to inter-decadal climate variability, including the entire Earth system dynamics, and 5) comprehensive evaluation of the consequences of engineering techniques and public health measures for mitigation and adaptation of global warming processes and their impacts.

3.4 Earth's Past Climate Changes as Window into the Future

Before humans began emitting greenhouse gases into the atmosphere, causing our planet to warm, global climate barely varied over the past 10,000 years. Now, Earth's climate may be on the cusp of rapid change. Fortunately, Earth's climate history contains plenty of examples of stabilising feedbacks, gradual change, crossing critical thresholds, and climate variability. Reconstructing this history in great detail using so-called climate proxies from a variety of geological archives will allow us to explore how Earth system components interacted at critical climate intervals in the geological past. Ever-improving analytical methods and proxies combined with modern Earth System modelling, network theory, and dynamical systems approaches will reduce uncertainty in projections of future climate and global environmental conditions.

State of the Science

Some consequences of global warming, such as sea level rise or more frequent and intense floods and droughts, can be predicted—within bounds of uncertainty—by climate models. However, the more severe consequences that could result from positive

Global evolution of temperature and CO_2

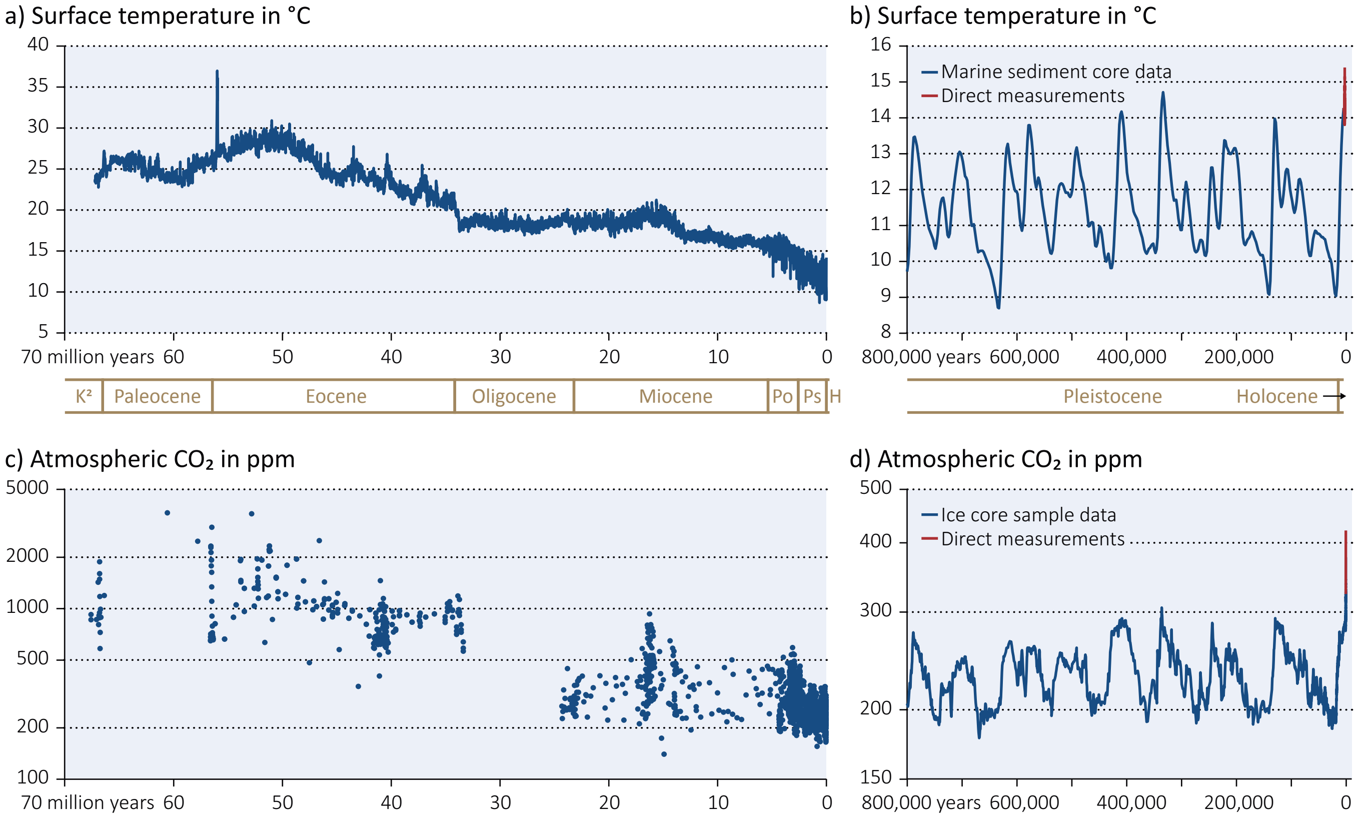


Figure 10. Top row: Proxy-reconstructions of the global temperature evolution for Cenozoic times based on oxygen stable isotope measurements in foraminiferal shells (70 Ma, a) and for the glacial cycles during the past 800.000 years of the Late Pleistocene and the Holocene (b), derived from oxygen stable isotopes in ice cores. Instrumental records from the last 100 years are shown in red colors; the warming already exceeds the temperature range of the last 800.000 years of the glacial cycles during the Late Quaternary. Bottom row: Atmospheric CO_2 concentrations for the same intervals. (c)Reconstructed from stable boron isotopes measured in the shells of planktic foraminifera and (d) from gas inclusions in ice cores. In red the last 100 years measured CO_2 record. Figure after https://paleo-co2.org/, Lüthi et al. (2008), Westerhold et al. (2020), Keeling et al. (Scripps CO_2 Program Data).(2008), Westerhold et al. (2020), Keeling et al. (Scripps CO_2 Program Data).

feedbacks in the Earth System, or crossing of critical thresholds, are much harder to predict. This is due to the nonlinear, sometimes cascading effects that characterise complex systems like the Earth's climate system. Investigations of periods of rapid or abrupt climate change in the geological past provide important information about how components of the Earth System interacted during those periods. Records of past change are found in sediment cores recovered from the bottom of the ocean, terrestrial archives such as lake sediments and speleothems, and in ice cores.

While the geological record contains evidence that global climate has varied throughout Earth's 4.5-billion-year history, the most detailed climate reconstructions can be made starting with the Cenozoic, an era that began some 66 million years ago with a mass extinction that ended the reign of the dinosaurs and initiated the age of the mammals (Fig. 10).

Climate cooled substantially through the Cenozoic. During the early Cenozoic, deciduous trees and reptiles were present even at the poles. Roughly 50 million years ago, cooling began at the poles, and by 35 million years ago, Antarctica was rapidly covered with ice sheets that remain to this day. Globally, forests began to give way to grasslands, transforming animal life and eventually leading to the rise of upright primates. By 2.7 million years ago, the Northern Hemisphere began to support extensive glaciation, coinciding with the development of ice age cycles paced by Earth's orbital parameters. What triggered the cooling is unknown; most current proposals relate to an increase in the efficiency of rock weathering, a process that removes CO_2 from the atmosphere, due to continental collisions and ensuing mountain uplift.

Against the backdrop of overall global cooling during the Cenozoic, periods of (sometimes rapid) climate warming have been identified. For example, 56 million years ago, abrupt warming of up to 9°C above background temperatures occurred that lasted for 100,000 years. This so-called Paleocene/Eocene Thermal Maximum (PETM) is thought to be associated with the release of massive amounts of carbon-based greenhouse gases (carbon dioxide and/or methane) into the atmosphere at a scale comparable to (but lower than) today's fuel-driven CO_2 emissions. Other periods witnessed longer-term warming, such as the so-called Mid-Miocene Climate Optimum roughly 15 million years ago; increased CO_2 release from volcanoes has been posited as the cause of this warming event. Even at their most rapid, these natural increases of atmospheric CO_2 were slow and modest in comparison to the recent and still ongoing rapid and dramatic fossil fuel CO_2 emissions; yet even their profound impact on climate is unmistakeably documented in the geologic record.

At several times during the Cenozoic, the Earth System reached—and crossed—thresholds that ushered in a new climate state. Glaciation of Antarctica and the Northern Hemisphere continents at about 35 and 2.7 million years ago, respectively, are among multiple signs that Earth's climate can cross thresholds that lead to dramatic modification of the global environment. The ice age cycles of the last 2.7 million years, defined by the waxing and waning of Northern Hemisphere glaciation (ice ages and interglacial periods), demonstrate the importance of amplifying feedbacks in the climate system. Cyclic changes in Earth's orbital parameters clearly trigger these ice age cycles, even though orbital changes have negligible impact on the amount of solar radiation that Earth receives. Thus, the orbital cycles must engage feedbacks internal to Earth's climate system to produce the observed dramatic changes in climate and land ice.

Two feedbacks of importance involve Earth's reflectivity, as impacted by ice cover and changes in the land biosphere, and atmospheric CO_2, as controlled by the ocean's sequestration of CO_2 in its deep waters. Both feedbacks operate with adequate rapidity to play a role in ongoing human-driven warming, so our ability to simulate these feedback's past behaviour is important for climate projections into the future. This brief account of Earth's past contains several examples of Earth system components where amplifying feedbacks were triggered by small forcings but have led to abrupt and possibly irreversible change once a critical threshold in the climate forcing is exceeded. Potential candidates for these so-called tipping elements that potentially severely disrupt global climate in the future include the stability of polar ice sheets and global thermohaline ocean circulation, as well as large-scale biosphere components such as the Amazon rainforest (Fig. 11).

In the framework of Earth System Science, the accurate reconstruction of the climate instabilities of the past, including the identification of feedbacks and potential tipping points, plays a key role in several respects: they serve to derive hypotheses as a basis for the development of complex climate system models, which in turn aim to estimate future climate trajectories. At the same time, high-resolution data from the past can be used to test the extent to which climate models are able to correctly predict a) known past events or b) the present from past proxy data. Earth System Science studies strongly benefit from such advances in modelling capabilities and the increasing number and quality of proxy data from geological archives. However, uncertainties remain regarding the various systems' proximity to tipping thresholds, and even more importantly how tipping elements interact, potentially triggering tipping cascades.

Key questions

Some of the key questions that can be addressed are as follows.

What drives changes in Cenozoic climate?

Can we simulate Cenozoic climate states and the transitions between states with what we know from the geological archives about climate forcing of that time? Reconstructions of atmospheric CO_2 over the Cenozoic generally support the greenhouse effect as one of the key processes affecting climate. However, in detail, there are multiple cases where CO_2 and climate variations appear uncoupled. Are these mismatches real, and, if so, what do they tell us? Are we underestimating the importance of changes in major components of the climate system, such as changes in Earth's cloud cover?

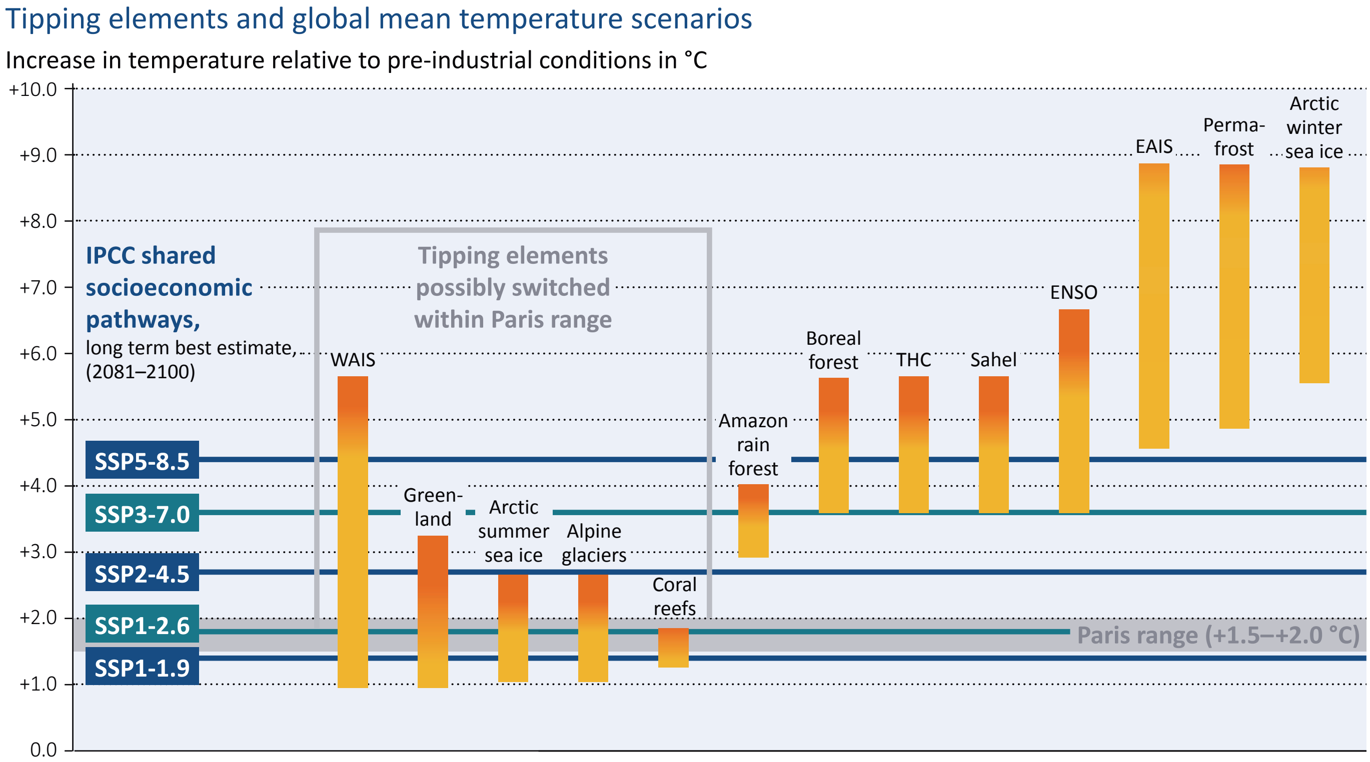


Figure 11. The critical thresholds for tipping points with respect to the Paris climate limit (global warming limited to below 1.5-2.0 °C temperature increase). At these critical thresholds, the present climate system may be fundamentally destabilized. Within the columns, colors indicate the probability for a significant change (from medium probability (yellow) to high probability (red). THC – thermohaline circulation; ENSO – El Niño – Southern Oscillation; EAIS – East Antarctic Ice Sheet; WAIS – West Antarctic Ice Sheet. The International Panel on Climate Change (IPCC) Shared Socioeconomic emission Pathways (SSP) project future global warming. The numbers indicate radiative forcing for various emission scenarios and range from low emissions (SSP1-1.9) to a worst-case scenario (SSP5-8.5). Current emission pledges suggest that humanity will embark onto at least the SSP2 pathway, which means that Earth will lose ice mass from the West Antarctic and Greenland ice sheets, Arctic Sea ice, and mountain glaciers. In addition, coral reefs will decline precipitously and, possibly, the Amazon Forest will reach its tipping point. Figure after Schellnhuber et al. (2016).

Are climate states repeatable in Earth history?

How much and how fast will Earth's atmosphere warm under a given forcing? One means to answer this question is to infer potential future states of the Earth System from the past. For example, could the future Earth attain the warm climate of the early Cenozoic under high CO_2 emission scenarios? Or are there aspects of the modern Earth (e. g., the configuration of continents and ocean basins, and the multitude of anthropogenic drivers) that would prevent this? If climate states are repeatable, then the "equilibrium climate sensitivity", the mean global surface temperature increase per doubling of atmospheric CO_2, can be reconstructed from paleoclimate proxies. Over the long timescale covered in these reconstructions from geological archives, we can assume equilibration of the ocean and ecosystems with the forcing. In the warm Pliocene era (5.3 to 2.6 million years ago), when sea levels were 12-32 m higher than today, geochemical isotope proxies inform us that the global mean temperature was about 3°C higher than in the pre-industrial Holocene, with CO_2 concentrations around 450 ppm. This results in a climate sensitivity, the increase in mean global temperature per doubling of atmospheric CO_2, of 3.0-4.4°C. In contrast, the "effective climate sensitivity", the present, transient ocean response to warming over the last decades (i. e., not including longer-term feedbacks) computed across dozens of climate models[7] for the modern Earth projects 1.8-5.6 °C per CO_2 doubling.

---

[7] Meehl et al. (2020).

What are the limits in carbon pool capacity?

Will the terrestrial biosphere continue to absorb fossil carbon, at what rate, and to what maximum capacity? The answer depends on how future biomes will respond to CO_2 and temperature change and how rainfall patterns will shift under global warming. The Cenozoic, and the last 10 million years in particular, provide many examples of shifts in the terrestrial biosphere emerging from the interaction between climate and biosphere; examples include the varying strength of the Asian and African monsoon systems. Similarly, how much more excess carbon and heat can the ocean absorb? The overturning circulations of polar oceans, including the North Atlantic Ocean and the Southern Ocean, and changes in the carbonate chemistry and the marine biosphere, are suspected to be instrumental in carbon and heat uptake. There is also strong evidence of large-scale changes in deep ocean circulation over the glacial cycles of the last 2.7 million years, making their study particularly relevant to a future that may include rapid and strong global warming.

How can we best explore critical thresholds and tipping points in the Earth system?

The combination of proxy data, theory, and Earth System modelling has the potential to identify critical climate system thresholds, and moreover, develop early-warning indicators for assessing the risk of approaching tipping points. Recent progress in the theory of dynamical systems, for instance, has brought forward new methods that can be used to signal that certain parts of the climate system are approaching tipping points. In addition, the assimilation of data into Earth System models has proved useful tool, the so-called emergent constraints, to narrowing uncertainties in climate change projections through empirical relationships relating the long-term climate response in a model to observable metrics.

How does the interaction of tipping elements affect the overall stability of the Earth System?

What is the potential for triggering tipping cascades in the Earth System? Given our knowledge of geosphere and biosphere feedbacks, is there a planetary threshold beyond which it will not be possible to stabilise global mean temperatures at intermediate levels? Although such a planetary threshold would be without precedent in Earth's Cenozoic history, earlier periods when large-scale volcanic eruptions emitted massive amounts of carbon dioxide into the atmosphere may provide extreme end-member scenarios for comparison with the present. Such periods include the Permo-Triassic boundary around 250 million years ago, or the Neoproterozoic when 'Snowball Earth' occurred at least three times between roughly 750 to 600 million years ago.

What is needed?

Advancing Earth System Science critically depends on the availability of relevant proxy data and on the model-based interpretation of data. Continual improvements to proxies and models will result in climate reconstructions that have ever better temporal and spatial resolution, spatial coverage, and accuracy. Additional enhancements will include increasing the range of climate-relevant parameters used in reconstructions, such as past temperature, salinity, pH, and nutrient concentrations. Such reconstructions will yield data-based constraints not just on the history of climate but also on its controls, consequences, and feedbacks.

The physical understanding of climate is one goal of Earth System Science. Proxy data used to reconstruct past climate changes have to be interpreted using climate system models, which are based on fundamental laws of the flow of energy and matter and semi-empirical laws of ecosystem processes. In turn, proxy data are employed to evaluate, and perhaps validate, Earth system models used to make climate projections. Advances in high performance computing and computer science have the potential to revolutionize our ability to harness proxies of past climate and environmental change to assess potential future scenarios under alternative paths of global human behaviour and economic development.

Given our knowledge of past rapid or abrupt changes in the Earth System and the unprecedented human influence on climate, it is imperative to identify tipping elements and assess the potential for crossing tipping points and assess the risk of triggering tipping cascades in the future. To capitalize on the wealth of Earth System data available for climate modelling and reconstructions, we need to bring together new approaches from dynamical systems theory, network theory, and machine learning.

3.5 The Anthropocene

The recent phase of unprecedented, rapid Earth System transitions, called the Great Acceleration, marks the beginning of the Anthropocene. In this new geological epoch, humankind constitutes the largest driver of change on Earth. Humans are making an imprint on the Earth System that is significant, measurable, and may cross thresholds that put Earth System stability at risk at a pace that is faster than human civilisations can adapt. Yet it remains essential to gain a deeper understanding of the societal challenges of the Anthropocene and develop potential mitigation and adaptation solutions and actions. Thus, we need a more transdisciplinary perspective and novel approaches to identify physical, ecological, and societal thresholds and avoid crossing them to shape a future in which the next generations can thrive.

State of Science

The increasingly dominant impact of human activities on the Earth System led Nobel Laureate Paul Crutzen in 2002 to propose a new geological epoch, the **Anthropocene**. Earth's global climate remains within the bounds of the Pleistocene interglacial trajectories. At the same time, human perturbations now exceed – in pace and scale – the shocks and stresses caused by natural processes such as solar radiative forcing, earthquakes, and volcanic eruptions, and others that have regulated Earth's oscillations between Ice Ages and Interglacials. The Anthropocene constitutes a manifestation of new pressures (forcing) exerted by humans on the Earth System. The climate system has not yet crossed a hard threshold that would propel the Earth System into a new state. However, there are indications that Earth is following a trajectory that will shift its climate away from relatively stable interglacial Holocene-like conditions. If global warming continues and Earth loses its climate resilience, climate thresholds may be crossed, moving Earth into a new state and triggering self-reinforcing feedbacks and potential cascading interactions.

The onset of the Anthropocene is proposed to have occurred around the 1950s, when there was a shift from a linear to exponential rise in human pressures on the Earth system, termed the Great Acceleration (Fig. 12). The main drivers of the Great Acceleration are the rapid growth of modern industrialised and fossil-fuel driven economies combined with a rapidly growing world population, where a minority of the world population reaps the largest benefits of economic growth. The consequences of the Great Acceleration for the Earth System are, amongst others, biodiversity loss, global deforestation, overexploitation of global fisheries, nitrous oxide emissions, and climate change. The wealthy world regions with stagnating population growth are responsible for the bulk of past and current greenhouse gas emissions. To provide basic functions, services and resources of nature for the well-being of the global society, projected to reach a population of about 10 billion people by 2050, will require rapid transformations of critical human, societal, and economic activities.

The Holocene so far has been a remarkably stable inter-glacial period, during which humans were able to develop agriculture, urban cultures, and our modern societies that are based on advanced technologies. Atmospheric temperatures on Earth oscillated between plus/minus 1°C around the global mean surface temperature of 13-14 °C during the past 10.000 years. Due to the burning of fossil fuels and land use change, global mean temperatures have already increased by 1.2°C, which means that we have now surpassed the warmest temperature on Earth since we left the last ice age. Climate models project that if the implementation of global mitigation efforts fails, the average global temperature increase will surpass 2°C in the next few decades, a global mean temperature that Earth has likely not experienced during the entire Quaternary. In addition to temperature, unprecedented rates of changes in many of the biogeophysical cycles have been observed. For example, the use of agricultural fertilizers has doubled the amount of reactive nitrogen in ecosystems, altering the nitrogen cycle. The ocean has absorbed so much of the excess CO_2 in the atmosphere from fossil fuel emissions that it has caused its pH to decline, changing the chemical balance of the ocean. Current species extinction rates are pointing to the possibility of a sixth mass extinction (an extensive decrease in biodiversity) in Earth history. We are approaching 1 million extinctions of the 8-9 million known species on Earth, and since 1970, wildlife population sizes have declined by 68%. Never in the biological evolution of our planet has a global mass extinction been caused by one single species.

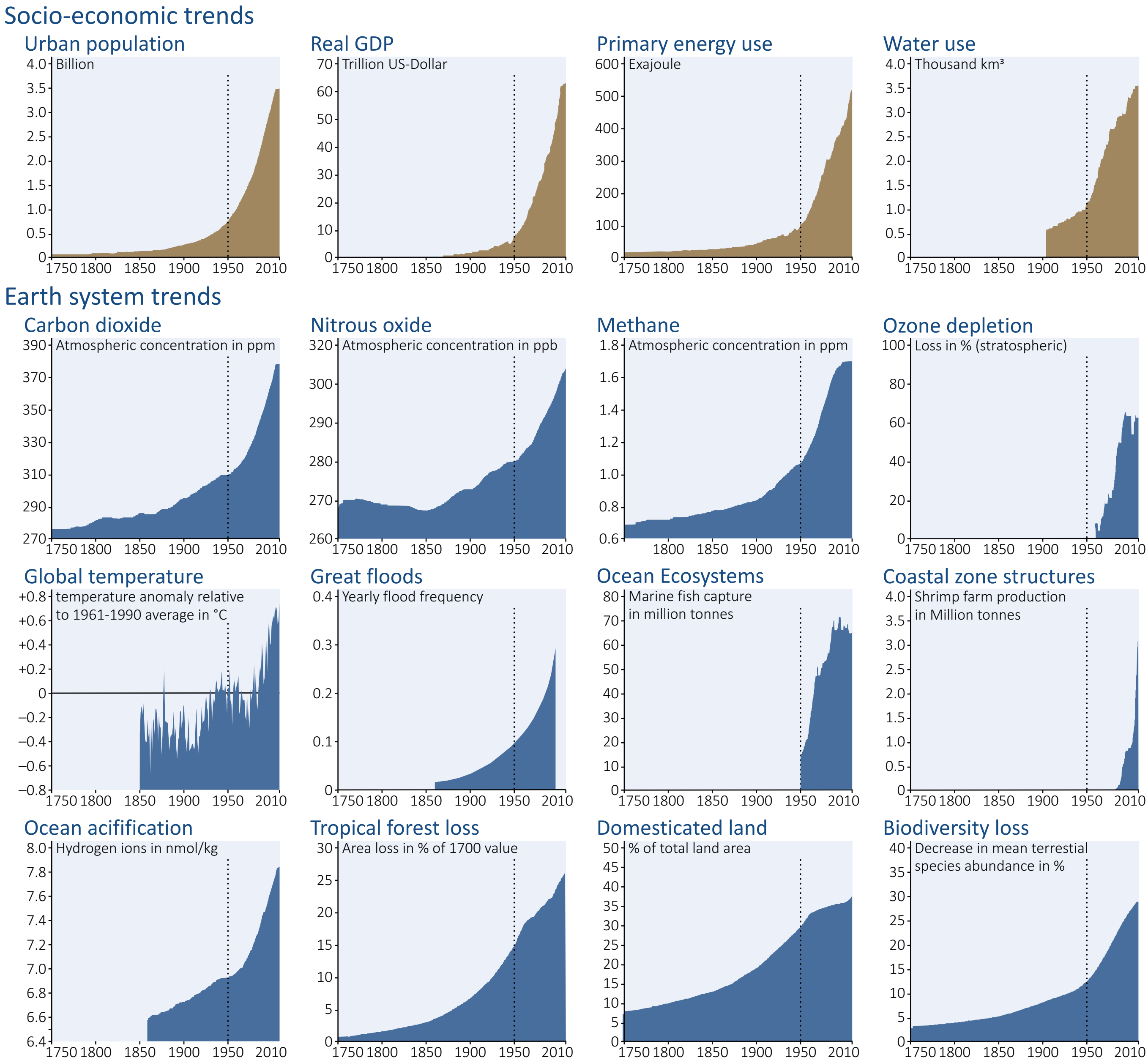


Figure 12. The “Great Acceleration” defines the onset of the Anthropocene as the early 1950s. At that time, many Earth system properties that began to rise exponentially above the relative stability of the Holocene epoch. Similar increasing trends of socio-economic indicators are also observed. Figure after http://www.igbp.net/globalchange/greatacceleration.4.1b8ae20512db692f2a680001630.html.

The **planetary boundary** concept (Fig. 13) provides a scientific framework for defining the biophysical systems and processes that contribute to the regulation of Earth System state. For each of these processes, it attempts to quantify a safe target or boundary including, for example, the N/P cycles, the water cycle, aerosol loading, climate, biodiversity, and land systems. If any part of the Earth System crosses these boundaries there is a high risk of triggering interactions and feedbacks that may lead to exceeding thresholds resulting in non-linear dynamics that put Earth System stability and the planet's ability to provide safe conditions for human civilisations at risk. If the Earth System can be kept within these boundaries, there is a high likelihood that Earth's climate regulating systems will remain with Holocene-like, stable interglacial conditions.

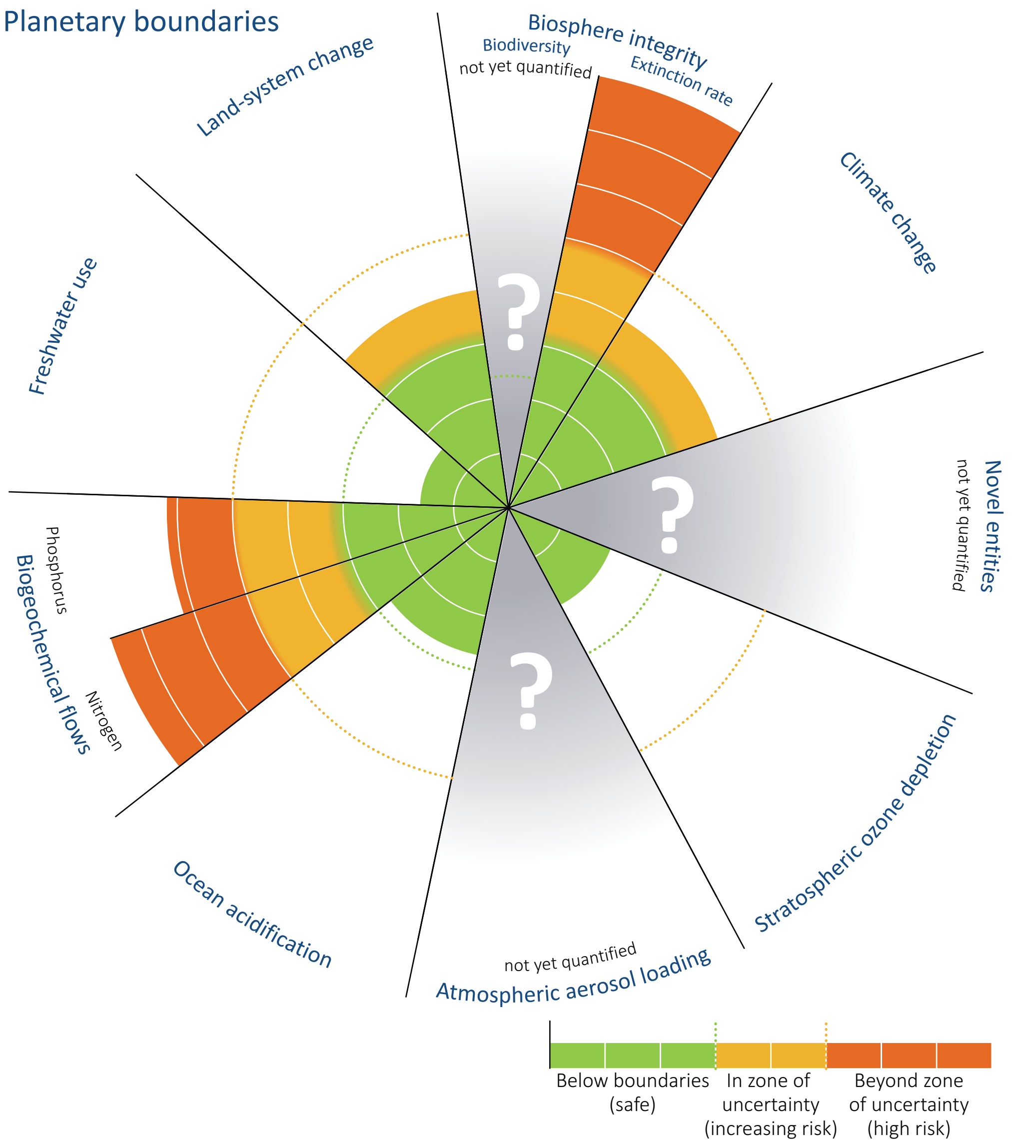


Figure 13. The critical planetary boundaries that define a "safe operating space for humans". A planetary boundary is a zone in which the state of a subsystem approaches a tipping point or a zone of strong risk increase (see section 2) such that minor additional forcing may result in a large and possibly irreversible response. The green zone is the safe realm. The yellow represents the zone of uncertainty (increasing risk), and the red is a high-risk zone. These zones are defined by the thresholds for stability of a given subsystem. Processes for which global-level boundaries cannot yet be quantified are represented by grey wedges. Figure after Steffen et al. (2015).

Safeguarding the resilience and stability of the Earth System, and thereby the functioning of all life-support systems, is a prerequisite for securing future well-being for humankind. Crossing planetary boundaries will put social stability, human health, and human well-being at risk. New challenges will also emerge, such as how to share the remaining ecological space on Earth such as carbon sinks, clean potable water, land, minerals, and nutrient budgets in a just way, among all citizens, for present and future generations.

Key questions

What are the critical thresholds of key interconnected tipping elements of Earth's climate?

At our current state of knowledge, keeping global warming as close as possible to 1.5 °C seems to be the only option to minimize its adverse consequences. Yet, the coupled nature of the Earth System, with the possibility of cascading effects, can cause further tipping dynamics and makes self-propagating 'run-away' processes a real risk. How such cascades function and at what levels of Anthropocene forcing they may be triggered is one of the largest gaps in our knowledge (see section 3.3).

How can Earth System stewardship avoid the risks?

The relationship between the degree of human forcing and the plasticity and buffering capacity of many of Earth's subsystems is poorly understood. A fundamental question concerns the level at which social dynamics at a given time and location result in reaching critical thresholds in closely connected social-environmental systems elsewhere. An example is provided by the intensity of international food trade that is mainly controlled by a few key actors such as multinational companies and financial investors in industrial countries. This high-level control may weaken local farming and dietary diversity and make societies more dependent on a limited number of globally traded food items. This in turn contributes to less resilient and more unhealthy dietary practices that may be fragile in the face of climate and water-related extremes like droughts, floods, and freshwater over-use. Finally, the impacts will cascade across markets and regions, ultimately hitting local farming communities hard. Climate change and resulting effects on food prices and security are also connected to human migration and political conflict.

The challenges that arise from such cascading thresholds affecting interconnected social-environmental systems across scales are (1) developing and reconciling sustainable socio-environmental and institutional behaviour and decision-making as outlined in the UN sustainable development goals, (2) establishing a global sustainable governance system for social-environmental risk assessment and management, and (3) avoiding disruptive environmental changes that lead to crossing critical thresholds by employing technological and socio-environmental innovations . All these steps must be accomplished in a just and equitable fashion. Meeting these challenges will allow humankind to assume a role of stewardship of the Earth System, ensuring a sustainable trajectory within planetary boundaries.

What is needed?

To answer these key questions, a holistic understanding and a sound diagnosis of the social-environmental aspects of the Earth System three main courses of action are urgently needed:

1) To properly assess biogeophysical risks, we need to determine the tipping points of subsystems and the danger of crossing them. To gain a deeper understanding of the dynamics of the integrated Earth System. This requires improved and novel model architectures, increased computing power, better parameterization of critical processes, and better model calibration with abundant data collected from a large array of new near real-time observation systems. These data will be used to test and improve the fully scale-bridging next-generation Earth System Models Earth System Models, enabling us to recognize feedbacks, thresholds, and tipping points in the Earth System.

Currently, Earth System Models remain physically under-constrained and not fully capable of working across scales (local to global). This limitation is mainly due to the scale dependence of already implemented processes (e. g., atmospheric convection and clouds) but also due to poorly parameterized or even hitherto neglected elements (e. g., specific biological processes and functional diversity in ecosystems). Solving this problem by implementing ever more physical submodels, significantly increases computational costs. New generations of hybrid Earth System Models that combine physical-based core modules with machine learning machine learning tools can be computationally much more efficient. Such hybrid Earth System Models would have higher accuracy and spatial and temporal resolution and would be capable of identifying tipping points. To improve machine learning models, we urgently need to enhance and integrate our current observation capabilities. These new sensor networks must be cross-scale, fully autonomous, and heterogeneous and integrate the currently detached global-scale single-function networks (e. g., global operational meteorological network), localized multifunction sensor networks (such as interdisciplinary environmental observatories), and biosensor networks (e. g., smart biosensing devices for micro-organic air, soil and water pollution).

Quality-proven crowd-sourcing technologies using citizen science networks should be included. These observing systems shall also serve as an early surveillance and warning system for approaching known and newly detected tipping points.

2) Two approaches to mitigate global warming are currently envisaged: radiation management and negative CO_2 emission technologies, sometimes called “geoengineering”. We do not recommend using this term, because it raises the expectation that the Earth System can be safely “engineered” by humans. For this reason, this report does not support radiation management, the injection of aerosols into the stratosphere, or the increase of albedo by the generation of strato-cumulus clouds through dispersal of sea spray at high altitudes above the sea. Specific reasons are the short-term effect of these measures, the unknown risks imposed on the Earth System, and the moral hazard presented by societies’ potential anticipation of a resolution to the climate crisis by taking these measures rather than by focusing on emission reduction measures. In contrast, according to the IPCC projections, humanity is unlikely to limit global warming to 1.5°C unless substantial amounts of CO_2 (about 10Gt/yr) are withdrawn from the atmosphere. Thus, research on technical negative emission technologies (e.g., direct air capture linked to geologic carbon capture; biologically enhanced carbon capture and storage) and enhancing natural sinks (e. g., biochar formation and dispersal, enhancing soil organic carbon storage, enhancing weathering by dispersal of basalt powder onto croplands, and replanting seagrass) should be pursued with high priority. However, all these negative emission technologies must be continuously checked for possible unexpected adverse environmental effects, ethical issues (like diverting land use in tropi-

cal countries from food production into fast-growing biomass for biologically enhanced carbon capture and storage), and their energy consumption, and should be embedded in the economic development of an emission certificate trading system.

3) Biogeophysical risks and tipping points that are mediated by the biosphere are highly interwoven with societal tipping points. There is an urgent need is to include the human domain as a major planetary system in holistic studies of the Earth System. Because our knowledge of the present state and future trajectory of the anthroposphere is still in its infancy, we must explore when and which positive societal tipping elements are likely to achieve rapid transformative change. Such change may emerge in different sectors and lead humans to pursue sustainable trajectories, preventing the crossing of biogeophysical tipping points. Importantly, major undesirable societal tipping elements (e.g., related to collapse of societal complexity, political polarization, conflicts) that lead towards the deterioration of other Earth tipping elements must be determined.

Identifying examples for these types of societal thresholds can be a first step towards keeping essential social dynamics in balance, such as population and urban development, and the financial system, with special reference to global inequality and injustice, norms and values of human environmental behaviour including global governance, and environmental education and information feedbacks on best practice solutions. Because biogeophysical and socio-economic risks and tipping points are highly interlinked, the development of next generation Earth System Models must include the full dynamics of social-ecological networks. A framework that combines next generation social (World-Models) with biogeophysical Earth System Models must be developed including multi-agent and multi-level adaptive networks but also data-driven ML submodels, while submodels integrating socio-economic metabolism can warrant the link between the socio-cultural and the biogeophysical spheres.

3.6 Extreme Events, Risks, and Resilience in Complex Earth Systems

Extreme natural events threaten local populations and infrastructure. The occurrence and intensity of storms, droughts, floods, inundations, and landslides are likely to increase while other natural hazards such as earthquakes evade predictability. As we saw from the 2011 Japan Earthquake and the subsequent tsunami, coupled risks and cascading effects combine to massively increase damages and further enhance vulnerability, frustrate prediction, and hamper mitigation efforts. By accelerating scientific discovery through strengthening of observational and data analytical resources, we can better inform responses to natural hazards, guide future hazard reduction and develop solutions for mitigation and disaster resilience.

State of the Science

Although the number of potentially hazardous natural events is not changing significantly, human communities are becoming increasingly vulnerable to natural disaster due to increased population densities, especially in urban areas. As a result, the negative impacts of natural hazards on people are increasing worldwide (Fig. 14). The share of the gross domestic product affected by economic losses has stabilised in recent decades, but a growing body of evidence points to a significant increase in the impact of the largest meteorological and geophysical disasters over the same period. The source of greatest concern is this 'heavy tail' in the distribution of extreme event magnitudes and their potential impact. In fact, because of the exceptionally low probability of the most extreme events, these so-called 'black swans' run counter to our psychological expectation bias, which is determined by experience. Black swans generate the greatest damage because their risk scenarios are not included in preparation and infrastructure design (Fig. 15). A classic example is the 2011 Tohoku-Oki earthquake in Japan. A single earthquake with a maximum magnitude of 7.9 was expected in this region, – not one of 9.0 that, in addition, triggered a cascade of events including a tsunami and a nuclear power plant failure. Hence, a significant challenge to address is our expectation bias with respect to future risks combined with the increasing vulnerability of global populations to natural hazards as a result of rapid urbanization, economic globalisation, and the rise of the human technosphere. To meet this challenge, the United Nations Sendai Framework declares that the central tasks for Earth System Science should range from improving our understanding of the hazard to enhancing disaster preparedness – ultimately aiming for resilience building, the common thread of disaster reduction.

Extreme weather events

Since the onset of industrialization, human emissions have increased the amount of CO_2 in the atmosphere by 45%, resulting in an increase in our planet's surface temperature by more than 1°C since the late nineteenth century. The consensus of the scientific community is that global warming is linked to an increase in extreme weather events. For example, record-breaking monthly mean temperatures now occur five times more often as they would have without long-term global warming. Cold extremes are generally declining, but in some regions (notably northern Eurasia), dynamic changes have resulted in increasing outbreaks of cold polar air onto adjacent continents in winter. Extreme precipitation causing floods and landslides, as well as severe droughts and famine, also increase globally as the consequence of an accelerating global water cycle.

Existing observational data, while inconclusive, support a strong global increase in the incidence of category 4 and 5 hurricanes. In addition, global projections indicate rising seas, stronger storms with increased risk of coastal flooding, and an increase in heavy rainfall potential. Yet, according to the IPCC, the projection of climate change effects on individual regions does not only have significant uncertainty but is also likely to vary over time during the 21st century. Whether droughts or flooding become more abundant regionally or are less likely is relevant to developing appropriate preparedness. Our achievements in the accuracy of short-term weather forecasts are impressive, thanks to our dense global observational facilities and advanced numerical models of the climate system. In contrast, we still fail to provide a reliable projection of longer-term weather trends at local to regional scales. Likely, non-linear dynamics and the complexity of the climate system cause small fluctuations to increase tremendously in the models over longer periods, leading to strongly reduced predictive power.

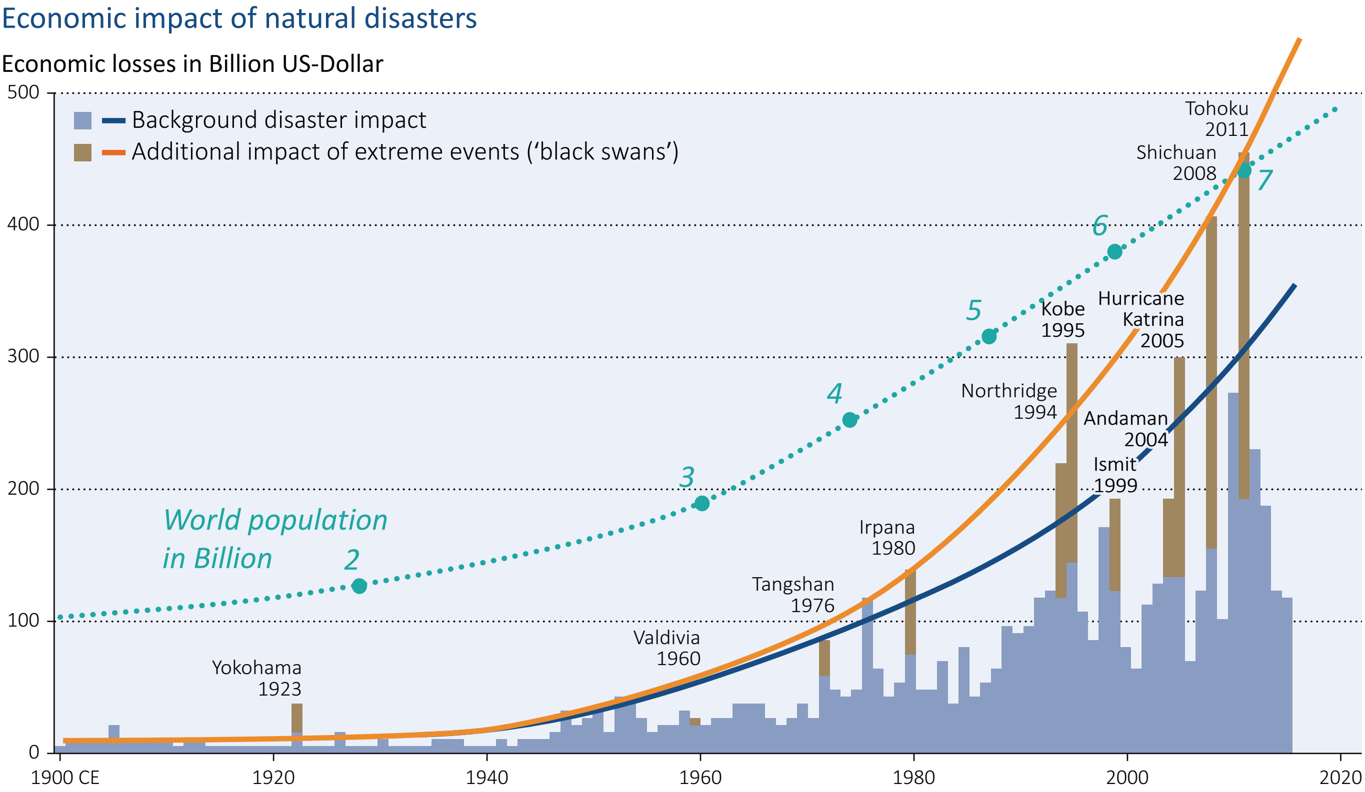


Figure 14. Economic impact of natural disasters. Bars in lower part of graph show increase of economic impact since 1900 (source Munich Re and CATDAT) in Billion US Dollars (corrected for inflation). The increase in losses reflects the increasing vulnerability of human communities, not an increase in events (with the exception of climate-related disasters in recent decades). Peaks in the event spectrum (brown bars) reflect extreme events ('black swans') such as the Kobe earthquake (1995), hurricane Katrina (2005), Wenchuan earthquake (2008), and the Tohoku-Oki and Christchurch earthquakes (2011). The growth of their impact (orange curve) strongly exceeds that of average disaster impact growth (blue curve). Dashed curve illustrates global population growth. Figure after Daniel et al. (2011).

Earthquakes: Forecasting the Unpredictable

While many extreme atmospheric events and volcanic eruptions have some degree of short-term predictability, large earthquakes do not. No reliable precursory phenomena to damaging earthquakes have ever been identified. In most cases, we have no direct access to the regions deep inside Earth where stresses build up to generate the next fault ruptures that lead to large earthquakes and the possibility of devastating tsunamis. The uncertainties associated with earthquake prediction pose substantial challenges for city planners and structural engineers striving to make life safe in regions of high seismicity – and for risk communication.

Recent developments in observational technologies, data processing, and process simulation are advancing the monitoring of Earth surface dynamics. Tens of thousands of sensors around the world, with some constantly recording background seismic hum and microseisms in addition to larger events. Scientists are now geodetically observing silent slip events taking place on faults that are not recorded on seismograms but that are still associated with earthquakes in a way hitherto unknown. Examination of microseisms and these 'silent' slip events has led to the discovery that Earth's crust will react quickly to even the smallest changes of stresses, mass transfer, atmospheric processes, deglaciation, changing permafrost boundaries, geothermal or other exploration activities, and melt migration inside volcanoes.

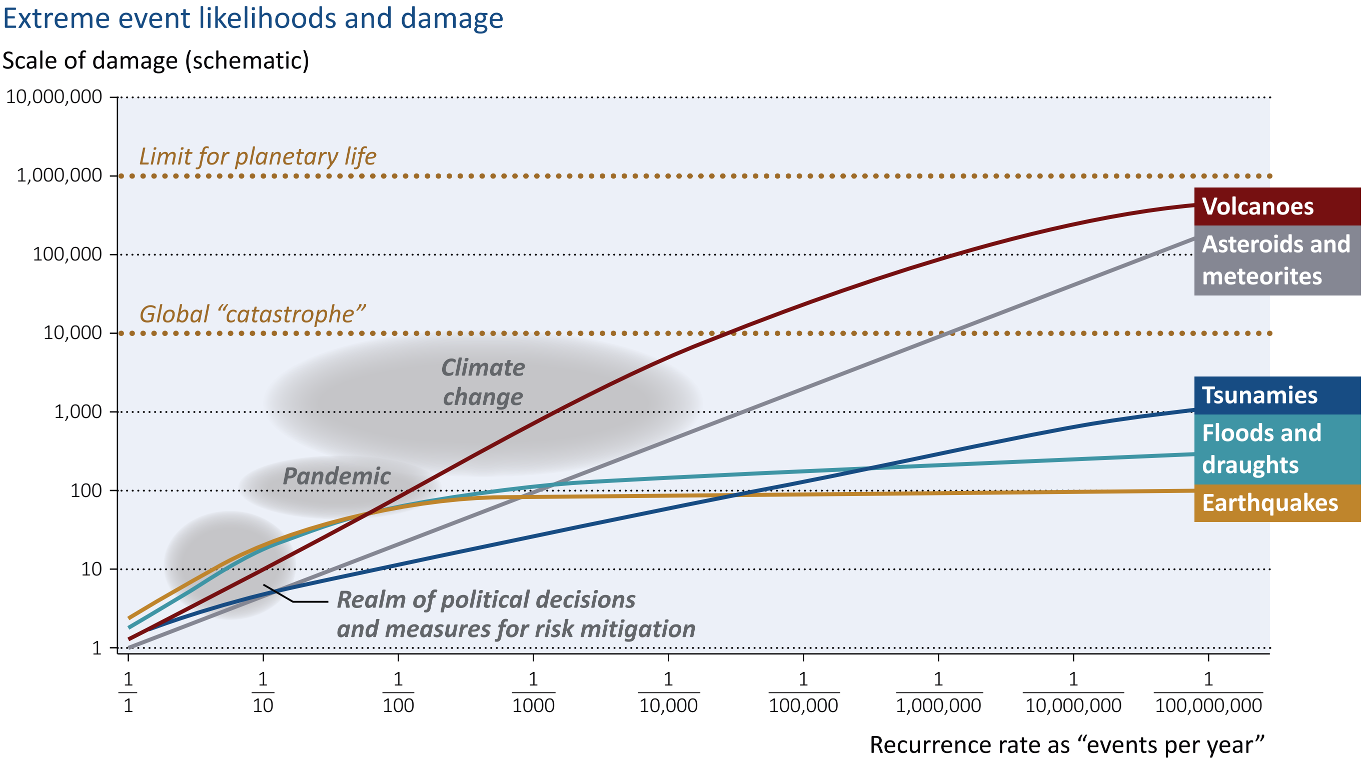


Figure 15. Extreme event likelihoods and damage; likelihood estimated from recurrence periods; disasters from asteroid impact or volcanic eruption may cause rare but more extreme damage events due to their global impact as compared to regionally limited disasters. The domain of political action and risk mitigation measures typically underestimates the scaling of damage and likelihoods. Figure after Plag et al. (2015).

Dense sensor networks and new sensing technologies (notably, the use of existing fibre-optic cables to measure ground motion with billions of sensing points) and data processing tools provide an opportunity to monitor minute changes in deformation inside Earth at short timescales. These technologies could be considered the first generation of structural health sensors and thus for estimating the tendency to release stress via earthquakes below our planetary subsurface. Challenges include managing tremendous volumes of data in near-real time, combining data from land-based and satellite-based systems, mining these multidisciplinary data sets with appropriate tools such as emerging data science methods, and using physics-based high-performance computing to enhance process quantification and predictive power from these observations.

Volcanic eruptions

The melting of rocks is one of the main ingredients of volcanism that played a fundamental role in the formation of continents, the emergence of life, and atmosphere and major environmental changes through geological time. Today, volcanic eruptions pose hazards and risks to human life, infrastructure, and short-term climate. The most violent past volcanic eruptions have affected the climate globally through their massive emission of ash, water and gases into the atmosphere. The Krakatau eruption in 1883, a volcanic black swan, not only claimed the lives of many tens of thousands of people through a tsunami triggered by the event, but also changed the global climate for a period, which led to significant crop failures and ensuing famine worldwide. Similar effects were observed after the 1815 Tambora eruption, and future eruptions of similar size and effects will occur on centennial timescales. The complex feedbacks between volcanic sulphur-oxide loads in the upper atmosphere, subsequent temperature changes, and the duration and impact of long-term climatic response after large volcanic eruptions are not fully understood. Thus, any attempts at radiation management by artificially injecting SO2 into the upper atmosphere (geo-engineering) entails incalculable risks.

We must better constrain where, when, how strong, and for how long volcanic eruptions will impact lives, infrastructures, economy, and climate. This requires new computational and statistical analysis methods to establish how magma evolves, ascends, and erupts, making volcanic monitoring a data-rich discipline. These tools will allow identification of reliable eruption precursors, such as volcano deformation, local increases in low-frequency earthquakes, or changes in the composition of gases emitted prior to eruption. Early warning requires linking geophysical observation with petrological and geochemical observations. Experimental studies promise progress in determining critical states of magma reservoirs, whether they contain eruptible magma, and what triggers eruptions. Important frontiers include physico-chemical investigation of the residence times of magma in a reservoir prior to eruption, advanced methods to record and predict magma physical properties, phase change, and degassing processes. Greatly enhanced observational capability with sophisticated automated data analysis and modelling capacities will advance effective early warning.

Space Weather

Planet Earth is embedded in the solar wind, a stream of high-energy particles that originate in our Sun. Solar activity controls its properties and dynamics. The interaction region of the solar wind with Earth’s magnetic field forms the magnetosphere. Together with the atmosphere, the magnetosphere represents a natural shield against harmful high-energy particles. So-called coronal mass ejections (CMEs)—giant eruptions of plasma at the Sun’s surface—deliver to interplanetary space vast amounts of energetic particles, usually more than 1 billion tons, at velocities easily reaching 3,000 km/s. CMEs occur at rates of one per day, depending on the solar cycle.

If a CME hits the magnetosphere, a geomagnetic storm occurs, with drastic consequences for Earth’s technical infrastructure. Space weather is the overarching term describing the plethora of physical processes initiated in the magnetosphere and ionosphere. The extreme space weather event in October 2003 led to large magnitude and rapid magnetic field variations, and significant increases in energetic electron and proton fluxes in the near-Earth environment, resulting in severe impacts on global communication systems, power supply, and the Global Positioning System.

Near-Earth space has become an important part of the human technosphere. The global navigation satellite system and timing services are most vulnerable to extreme space weather events. Perturbations or even disruptions of power supply due to extreme magnetic field variations endanger future smart city and smart economy concepts. Hence, increased physical understanding of space weather effects and their consequences for the proper functioning of advanced technologies are essential. This knowledge is the basis for our societies making forecasting space weather events a major challenge for basic and applied space research.

What is needed?

In an Earth System Science framework, what actions should be taken to inform responses to natural hazards, guide future hazard reduction, and develop solutions for mitigation and disaster resilience? While considering the appropriate actions, it is important to communicate two key messages. First, extreme events can trigger subsequent disasters in a cascade of events. Examples include an earthquake that is followed by a tsunami that is followed by an epidemic or a major flood that is followed by landslides causing infrastructure to fail, which is then followed by famine, all entailing major economic costs. Second, the human response required after most of these extreme events and disasters, or cascades thereof, are likely the same, regardless of their specific nature. Hence, the increasing vulnerability of our infrastructure, economy, and technosphere will have to be met with enhanced foresight. Resilience building must be a fundamental strategy to mitigate risks and reduce damage. Several recommendations follow.

Monitoring

- Substantially extend our observational infrastructure to monitor the nucleation processes of extreme weather events. Such monitoring shall include detecting changes in the number of extreme weather events and artifact-free analysis of tropical storms from satellite imagery and, for example, high-resolution radar.

- Extend our observational infrastructure to be able to monitor the processes leading up to large earthquakes and develop appropriate early warning strategies.

- Use the geological record of earthquakes, volcanic eruptions, climate fluctuations, and surface processes (e.g., droughts, landslides) to better estimate the magnitude and recurrence times of past extreme events, placing particular emphasis on the detection of rare black swans and their impact. This knowledge will inform predictions of extreme events.

- Enhance our capacities to monitor active volcanic regions, making use of new remote sensing methodologies. These tools will allow us to monitor precursor activity at the surface to improve prediction and risk evaluation and identify active volcanoes in critical states before an eruption.

- Develop novel methods to handle, process, and analyse increasing amounts of data from remote sensing and other monitoring sources.

- The necessary computational infrastructure will require substantial investment to maintain and extend German institutions' leadership role in these important Earth System Science endeavours.

Model building

- Develop mechanistic models (e.g., high-resolution, convection-resolving models) and projections of the global water cycle, including flood and drought events under changing climate states. Use the knowledge from past events to project future weather extremes, including tropical cyclones as well as smaller-scale extreme events like severe thunderstorms and tornados.

- Using neural network approaches, for example, to link climate projections to data collected on land use and rural or urban development, permafrost change, and slope stability for the prediction of landslides and their potential impact.

- Harness data science and high-performance computing tools to mine the very large seismo-geodetic data sets to improve earthquake forecasting and early warning systems.

- Develop strategies from experimental and analytical petrology as well as geochemistry and geochronology, and us data science approaches and simulation technologies to infer the volume, depth and duration at which magmas reside in crustal reservoirs, determine critical states of activity, and – ultimately – understand what triggers volcanic eruptions.

- Use observations from space to model and predict ash cloud and toxic gas dispersal in the atmosphere to reduce its impact on air travel and health.

- Advance understanding of the impact of extreme space weather on space and terrestrial infrastructure.

- Develop scenarios and build hazard and risk models to improve hazard mitigation that reflect both the historical record and the human psychological bias to overlook or underestimate the occurrence of extreme events. These models need to include scenarios for vulnerability, societal response, and resilience that consider geoscience as well as the psychological reaction to and economic ramifications of natural disasters.

- Resources will be needed to support services that provide essential data and data products to the wider Earth Science community. Resources are also needed to equip the Earth Science community with sufficient computing power to exploit emerging simulation and big data tools.

Managing

To meet the priorities of the Sendai Framework on disaster reduction, the following requirements face the Earth System Sciences in the fields of early warning and adaptation measures:

- *Early Warning systems*. Extend and improve early warning systems by supporting further research and method development.

- *Communicating disaster and risk*. Develop appropriate strategies and tools to communicate to stakeholders and the public to effectively manage risk. Communications include regular updates of information on the global distribution of hazard types, hazard risks and their magnitudes in time and space, and early warning of extreme events.

- *Advancing disaster literacy*. Strengthen public education activities to raise disaster literacy. Fundamental knowledge about hazards is indispensable for raising the level of disaster preparedness, mitigating the impact of potential disaster, and having proper emergency measures in place.

- *Building resilience*. Develop new strategies to build resilience considering society's growing vulnerability and risk from exposure of society and human technosphere and its infrastructures to hazards. To avert the consequences of natural disasters on our increasingly vulnerable economies and livelihood requires advances in technology and geotechnical engineering solutions, as well as improved predictive and early warning capabilities.

- *Networking sciences towards resilience building*. Form cross-disciplinary networks and partnerships between Earth System Science and the engineering, economic, social, and psychological sciences. Successfully developing strategies and programs for response and resilience-building will require integrated efforts across disciplines and exploiting international cooperation based on appropriate human and capital investment.

3.7 Resources

The "sustainable" use of Earth resources implies that our present needs do not compromise the ability of future generations to meet their needs. A shift towards sustainability is timely, as it coincides with two important developments. First, the world economies need to transition from fossil fuel- and nuclear-based energy production to renewables. Such a transformation requires the production of vast amounts of metals stored at Earth's surface and in deep geologic formations and the ability to store energy and its waste products below-ground. Second, humans are increasingly negatively impacting resources contained in Earth's surface "critical zone", such as soils and clean freshwater, which are the foundations of our livelihood. While Earth System Science may deliver the diagnosis of Earth in change, resource-related science may contribute to the cure – yet this cure needs to be based on socially and environmentally responsible principles.

State of the Science

Earth resources, whether they are extracted from rocks deep beneath our feet, lifted from the seafloor, or exploited as services at Earth's surface, are neither limitless nor renewable on human timescales. Nor does the use of these resources come without cost to the societies affected by their exploitation. Some resources, like fossil fuels, are now widely considered to impart an unacceptable cost on the entire global community in the form of the greenhouse gas CO_2 emissions. Yet our economic system requires ever-growing usage of these resources for the foundations of modern industrial and agricultural society. Even if a circular economy were in place at some point in the future, the required recycling of raw materials will never satisfy demand, and any leakage in the recycling loop will still need to be replaced by "fresh" materials. The recognition of this dilemma is demanding a change in our view of the use of Earth resources, with fundamental implications for our future economic system. It is at the heart of "sustainability" as defined in the UN sustainable development goals: "the use of Earth resources that does not compromise the ability of future generations to meet their needs."

This change in focus to sustainable use of resources is accompanied by major concurrent challenges: 1) If the Paris 2015 1.5°C warming goal is to be achieved, hydrocarbon resources will need to be fully phased out from the global economy by 2050. During this transition we will see the phasing-out of the use of coal, oil, and possibly wood, and the successive move to low-CO_2energy resources, first to hydrocarbon gas and then to green energy. 2) The paramount "energy transition", meaning the shift to renewable energy sources, requires a massive increase in the exploration, exploitation, and recycling of "critical" metals from rocks at depth in the Earth (where "criticality" is defined by both availability and supply challenges). 3) The public increasingly recognizes the severe negative environmental and societal impacts resulting from the extraction, use, and waste produced during the extraction of many raw materials. 4) The deep subsurface will be an increasingly important component in the storage of energy or of its waste products. 5) Humans do not only use resources, but human activity severely impacts the integrity of terrestrial Earth surface resources such as soils and freshwater.

Earth scientists are essential actors in satisfying the demand for Earth's resources required for the energy transition. However, they also need to be able to effectively communicate the risks and consequences of different resource exploitation and use scenarios.

Key questions

The ecological and economic challenges are most pronounced when focusing on the five resource types on which future humanity most depends. Three of these (energy, metals, and deep storage) are called here “geologic subsurface resources”, as they rely on extraction or use of geologic structures and materials up to several km depth. Two are called “Earth surface resources” (freshwater and soil), as their integrity is impacted by human activity to the extent that their provision as a basis for human life is threatened. Both types are linked through the “food-water-energy nexus”, whereby food and water supply are linked to energy production and storage. The focus in this chapter is on terrestrial geo-resources rather than the marine food chain (with a small detour into marine metal mining).

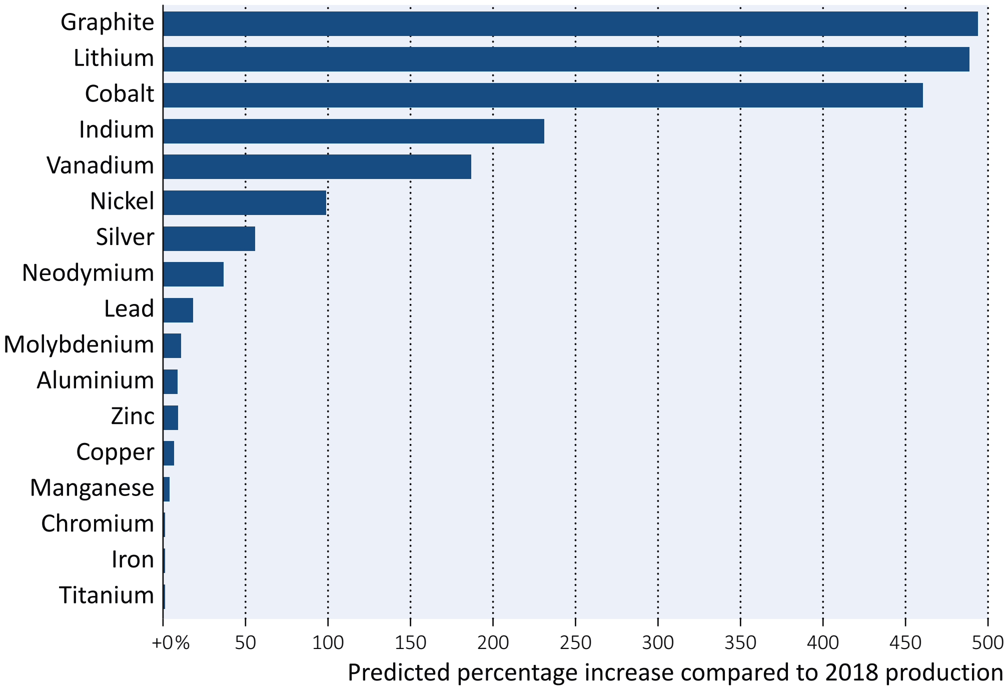
Can the supply of metals ensure a low-carbon future?

There will be a substantial resource cost associated with the renewable technologies required to transition to a low-carbon future; in this way, metal resources and climate change are inextricably linked. Yet, as pointed out in two assessments on carbon-free electricity production by the World Bank (2018 and 2020), the resource implications are largely overlooked in the decarbonization scenarios used in climate and impact assessment models (Fig. 16). This is surprising and, as a result, the Earth and Material Sciences have been saddled with a formidable research agenda. We explore these implications by looking at the three most prominent components of renewable electric energy: solar technologies, wind power, and energy storage.

A first challenge lies in the unknown climate pathway humanity embarks on: the current commitments made by governments in the Paris Agreement will increase total metal demand alone for a carbon free-electric energy production from about 40 million tons in 2018 to 95 million tons in the year 2050. However, these commitments will still limit warming to only 2.7°. In order to achieve the 1.5° global warming scenario, much more green energy capacity is needed and could require a total of 180 million tons of metal resources.

A second challenge in projecting demand is that it will be strongly influenced by technological developments, which can occur on relatively short timescales when compared to exploring for new metal resources. The metals that will be most in demand for renewable energy production are, in addition to large amounts of the major elements silicon, aluminium, and iron, the rare metals lithium, copper, lead, nickel, silver, gallium, selenium, chromium, manganese, cobalt, and zinc, and the very rare metal indium. If new direct-drive wind turbines are favoured for offshore infrastructure, demand for the rare earth element neodymium will increase. The electrification of transport will also require vast amounts of lithium, if lithium-ion batteries are used rather than other modes of energy storage like hydrogen-based technologies.

A third challenge arises because strategic decisions made by policy makers about which types of renewable energy production will be adopted influences metal demand. For example, metal demand is 2-3 higher for wind power and photovoltaics, and by up to a factor of 10 for energy storage. As one of the most prominent examples of energy storage, we look at the demand for lithium. Energy storage is projected to increase from ca. 3 GWh today to 20 GWh under the 2° scenario and 45 GWh under the <2° scenario, requiring a cumulative demand for Li of 5 million tons for 2° (a 500% increase relative to 2018) and 10 million tons for <2° by 2050. Todays’ annual lithium production is about 80,000 tonnes. In the absence of recycling technologies (at present Li has a virtually zero recycling rate), a six-fold increase in Li consumption is predicted alone in the next 10 years.



2050 increase in resource demand for carbon-free electricity production

Figure 16. The increase in global metal and graphite demand in percent by 2050 that is required for carbon-free electricity production in the 2° warming scenario.

The fourth challenge arises from unknowns in reserve estimates. In keeping with the lithium example, recognized reserves (according to the US Geological Survey) are currently 17 million tonnes. The total world resources of lithium are estimated to be about 80 million tonnes – sufficient to meet the 2° scenario and for a period of ensuing battery replacement. For many other metals such as copper we have seen that the ratio of production to reserves has remained relatively constant over the last 50 years; in other words, and for the time being, geologists and mining companies seem to be finding and developing copper mines as fast as we are using copper. However, to continue to meet demand, geological and geophysical methods will have a key role to play. Today, we have only explored and exploited the upper ~500m of Earth's crust at large scale. There is considerable potential at greater depth, but Earth scientists will have to find improved ways to explore the deep crust based on models for the mechanisms that enrich metals at depth.

Exploring enrichment processes in Earth's crust is crucial because most of these elements are present in common rocks only in minute amounts, as trace elements, rendering them subeconomic. However, Earth has done the first enrichment steps for us already. The distribution of metals in rocks is highly variable, depending on the source rock, the mineralization process, and the geotectonic setting. Enrichment factors between common rocks and metal deposits range between a factor of 5 for the major elements iron and aluminium, to a factor of 100 to 500 for trace elements such as copper and zinc. These enrichments are taking place deep inside Earth during magmatic processes, or at the surface during interaction with the atmosphere and the hydrosphere. But the deep ocean floor is also increasingly seen as an attractive future resource. Critical metal resources in the deep sea include copper, cobalt, nickel, lithium, platinum, tellurium, zinc, and many rare earth elements, having been enriched over millions of years in very slowly accumulating metal formations on the seabed. Metallic raw materials are associated with specific types of rock and sedimentary formations where they formed in specific geological settings and during certain geological periods. Continuing to explore the geological processes that concentrate metals and to further develop the technologies to image the deep Earth are thus very important. It is also essential to cultivate relevant expertise in deep Earth Dynamics and Earth's surface environment, invest in new analytical methods, and deploy geophysical exploration tools to disclose unknown reserves and new resource types. The shift in the types of elements we need to extract in the future will also rely on developments in the material sciences. That discipline will provide the expertise for extracting minerals of direct industrial use: zeolites as catalysers, mullite in high-performance ceramics, and rare earth oxides in superconductors and electricity generators.

Fortunately, this transition towards entirely novel metal exploration coincides with increasing sensitivity for sustainable development. As a result, for many metals, the most serious challenges to resource supply are not availability, but ESG (Environment, Social, and Governance) factors. First, mineral extraction for renewable energy will itself generate greenhouse gas emissions, estimated to amount to a cumulative 6% to those emitted from coal and gas generation by 2050. Metal extraction may significantly impact local ecosystems, water supplies, and communities. Mining of the deep sea threatens dark, cold, energy-poor ecosystems that are particularly vulnerable to mechanical disruption. Mining impact experiments confirm that even the soft sediment seafloor would take many decades to hundreds of years to recover from the disturbance caused by manganese nodule removal. In terrestrial environments, the mining industry is addressing these factors in a range of ways – by decreasing energy and water consumption, and by reducing emissions and other effluents to meet climate change and sustainability goals as expressed in the UN Sustainable Development Goal 12.2 „achieve the sustainable management and efficient use of natural resources“. However, the potential side effects of marine mining on marine ecosystems and food chains, especially to fisheries, is still widely unknown. A dialogue about future land and ocean mining must take place between the civil society that promotes clean energy and the resource-rich developing countries that will make large economic gains from mining. Geoscientists will have a key role in mediating meaningful dialogue.

Resources from outside of Earth are unlikely to help energy production or any other resource demand. A few private investors are evaluating the idea to mine asteroids, some of which can be rich in platinum-group elements, gold, and the rare earth elements – important ingredients for renewable energy production on Earth. The lunar surface is rich in Helium-3, whereas Earth is not, which might become essential should nuclear fusion become a realistic technology. However, the economic and energetic costs and the required technology for such space mining make this an unrealistic vision within the time remaining to decarbonize Earth's energy systems.

Subsurface geological technologies for energy exploitation and storage?
The deeper subsurface down to several hundred meters to kilometres depth will increasingly serve other novel purposes. Here we focus on three uses of deep geological structures: geothermal energy, subsurface energy storage, and deep disposal of radioactive waste.

Geothermal energy will be an important source for the future energy mix at the domestic level and in densely populated urban areas. One example is Munich's ground heat source and geothermal program. Future research will move this application from shallow heat exchange towards deep heat storage and high-temperature geothermal power generation. Geothermal plants will be built in intermediate, deep, and super-hot environments near active magmatic systems. The latter are already being developed, for example, in the Reykjavík metropolitan region of Iceland. Using deep hydrothermal energy will require hydraulic stimulation of reservoirs, which risks inducing seismicity. Research needs to be directed at avoiding this hazard while simultaneously communicating associated risk to the public. The aim is to keep the environmental impact of geothermal energy use as low as possible.

Subsurface energy storage will be increasingly important in renewable energy systems and will entail deep storage of large quantities of energy in the form of fuel, heat, and pressurized gas. The power-to-gas conversion concept means transforming excess energy from renewable sources into storable fluids. The greatest potential for deep storage exists for the high-energy density form of 'renewable' hydrogen and the methane synthesized from it. For example, the Netherlands announced the first large-scale projects that will combine wind power generation with hydrogen production and storage, utilizing existing gas distribution systems. These projects require close collaboration between engineers and subsurface specialists.

Geologic carbon storage in the subsurface may serve as a bridge to reduce atmospheric CO_2 en route to a low-carbon future. It is currently not in the focus in Germany, but elsewhere in the world it is gaining in importance. Geologic carbon storage involves the injection of supercritical CO_2 into the subsurface where it is physically trapped below an impermeable caprock. Over time, supercritical CO_2 is dissolved into subsurface fluids. The acidity of CO_2-rich fluids drives dissolution of the rock, releasing cations. These cations may react with dissolved CO_2 to form new carbonate minerals that trap CO_2 in a solid form that is stable over millennia.

The subsurface is also the most reliable and safe repository for heat-generating radioactive waste. Mapping out safe storage conditions underground that last over timescales of hundreds of thousands of years requires geological knowledge, experimental concepts, and simulation tools. The role of the geosciences is to identify "geological barriers", whereas the domain of the material and mineralogical sciences is to develop "technical barriers", which encloses the high-level waste. A long-term research strategy is required for evaluating the integrity of potential host rocks (e.g., in rock salt, clay-rich units or crystalline rocks) based on fundamental physical, chemical, and biological data. The goal is to predict their reaction with underground fluids and radioactivity during long-term storage. It will take 40 years or more to develop a safe radioactive waste disposal site, including addressing the concerns of the regional population.

A common prerequisite to developing any of these deep storage technologies is exploring the transport and reaction properties of fluids in upper crustal rocks. For example, in geothermal systems, the ability to maintain a conductive hydraulic network over the long term requires stimulation treatments. In contrast, a host rock for a nuclear waste repository requires the exact opposite — low or no-flow conditions. Understanding these same processes is critical for exploiting other resources, including mineral exploration.

To increase public acceptance of subsurface utilization in densely populated areas, risks and uncertainties need to be closely monitored, adverse side effects such as induced seismicity or drinking water contamination need to be minimized, and the risks needs to be openly communicated to the public.

How can a safe supply of freshwater for use by humans and for ecosystems be ensured?

Humans depend on clean freshwater for drinking, domestic purposes, food production, and industrial processes: so-called “blue water”. Terrestrial ecosystems, both natural and managed, depend on sufficient soil moisture and evaporative water flows: so-called “green water”. Several developments currently run counter to the sufficient availability of blue and green water. Achieving the UN sustainable development goals that demand providing basic sanitation and secure access to clean water for all people are therefore impaired: 1) most rivers are now highly managed, reducing their interaction with ecosystems and causing water shortages for local communities; 2) surface and groundwater resources are depleted in many regions due to excessive use and drought; 3) deforestation affects local water cycling with potentially adverse effects propagating to adjacent regions; 4) confounding these issues, global climate change leads to melting of glaciers reducing their storage capacity, longer and more intense droughts, more extreme rainfall events, and reduced freshwater availability in areas that are dry already; 5) population growth and water-demanding lifestyles of a rising middle class results in further increasing water scarcity—already affecting about two billion people. All these effects will be amplified in a future with present global economic growth scenarios. Conflicts over water resources will be more frequent. The development of shallow geothermal systems as an energy source will increase demand on water resources. New challenges will therefore arise by the need to safely produce energy while limiting impact on shallow water resources.

The terrestrial surface is also increasingly featured in concepts of so-called “negative emissions” – withdrawal of CO_2 from the atmosphere by technical interventions or by the enhancement of biological processes involved in the carbon cycle. In fact, negative CO_2 emissions of 10–20 Gt/year (ca. ¼ to ½ of current anthropogenic emissions) are factored into the IPCC projections for adhering to the 1.5° warming limit. Of these potential solutions, afforestation and bioenergy with carbon capture and storage (BECCS) will require massive changes to land use, impacting hydrologic and nutrient cycles and food production at a scale at which the impact to the Earth surface system and its social acceptance are difficult to gauge. Others, like soil organic carbon enrichment, are less invasive but may be hampered by questions of their permanency. „Enhanced weathering”—dispersing basalt particles on croplands to consume CO_2 during their dissolution while also fertilizing the fields—requires the mining, grinding, and transportation of gigatons of basalt powder per year—a scale that is a significant fraction of the global river sediment transport. All of these methods profoundly interfere with Earth’s sensitive regulation systems. The feasibility of these methods, and their economic, energy, environmental, and social costs, require intensive and urgent interdisciplinary research.

The "planetary boundary concept" offers guidance for placing these challenges into a scientific framework. However, the definition of a planetary boundary merely uses freshwater consumption as a proxy for human-caused disruptions to the water cycle. A more encompassing boundary definition should account for all key functions of freshwater in the Earth System. Model-based projections are the key tool towards this aim. However, current models predominantly treat the long-term, spatially averaged hydrologic impacts of global climate change. Next-generation global hydrological, land surface, and vegetation models should address the mechanisms and impacts of extreme events—particularly droughts. They should include both anthropogenic climate change or other, more direct human interventions, such as water withdrawal from surface and subsurface resources, and the effects of glacier melting and land use change. In particular, the latter two may be teleconnected over large distances, with impacts across regions and domains.

A second cornerstone is the integration of these combined hydrologic – Earth system models with remote sensing databases. Data from ground-based monitoring stations and other data continuously compiled by public authorities will be the basis of these models. Incorporation of satellite observations such as those from GRACE (Gravity Recovery and Climate Experiment) will allow quantification of changes in ice mass or freshwater storage. These data are valuable because groundwater is particularly difficult to monitor as aquifers are vast and unseen, yet groundwater meets the domestic needs of roughly half of the world's population. Analysis of such remote-sensing data should be expanded to enable determination of the effects of changes in freshwater fluxes and stores for the biosphere, including drought-related impacts on vegetation productivity and thus natural CO_2 sequestration. Furthermore, integration of model simulations and statistics on freshwater use across sectors should investigate solutions to emerging trade-offs within the water-energy-food-security nexus, for example, the competition for subsurface water between domestic use and energy production. Socio-hydrological analyses, a currently under-researched field, should be advanced to study social dynamics – operating at local to global scales – possibly leading to (or obstructing) more sustainable water futures.

How can soils of Earth's critical zone be protected in the face of climate change and human disturbance?

Soils, the thin, vulnerable layer covering 95% of the terrestrial land surface, provide essential services to humankind. Soils meet the demand for sufficient energy-rich food for a global population that may exceed 10 billion in 2050 and so alleviate the malnutrition that already affects 820 million people today. Soils provide essential micronutrients such as zinc and iron, the lack of which leads to the increasingly recognized "hidden hunger"- micronutrient deficiency, a major health problem that affects 2 billion people. Further, by impacting the infiltration of water, water storage, and runoff, soils are a key player in the global water cycle. Finally, through their soil-organic compounds, healthy soils can sequester a substantial fraction of anthropogenic atmospheric CO_2.

Despite the importance of maintaining soil quality globally, soils are being severely threatened by degradation. Soil degradation is already affecting 25% of the global land area, and by the year 2050 might rise to 80%, a point at which the environmental limit within which humanity can safely operate will be reached. Soil becomes degraded mostly due to two factors. First, about 30% of global soil is moderately to highly degraded through salinization, compaction, acidification, chemical pollution, and nutrient depletion. Second, soil erosion, which is the most serious threat, results mainly from poor agricultural practices. Many parts of the populated land surface are eroding at rates that exceed those of soil formation by one to two orders of magnitude. These developments place achieving the UN Sustainable Development Goal “End Hunger” at peril. This goal targets the need for all people to have access to sufficient and nutritious food year-round, ending all forms of malnutrition by 2030. Soil degradation will further impair planetary climate stability by reducing soils’ contribution to regulating the global water cycle and their ability to cleanse climate-sensitive trace gases from the atmosphere.

Soil research, placed into an Earth System perspective including the rocks below, the water within, and the bio- and atmosphere sphere above, has an important role to play in furthering the SDG “End Hunger”. A foundation of such research will be the critical zone (CZ) that extends from the top of the vegetation to the base of the groundwater level and considers a living, breathing, constantly evolving boundary layer where rock, soil, water, air, and living organisms interact (Fig. 17). Water and atmospheric gases move through the permeable CZ, and organisms thrive at its surface and within subsurface environments. The zone is “critical” because under stress its functions can break down entirely or shift to another state.

Monitoring in the Critical Zone

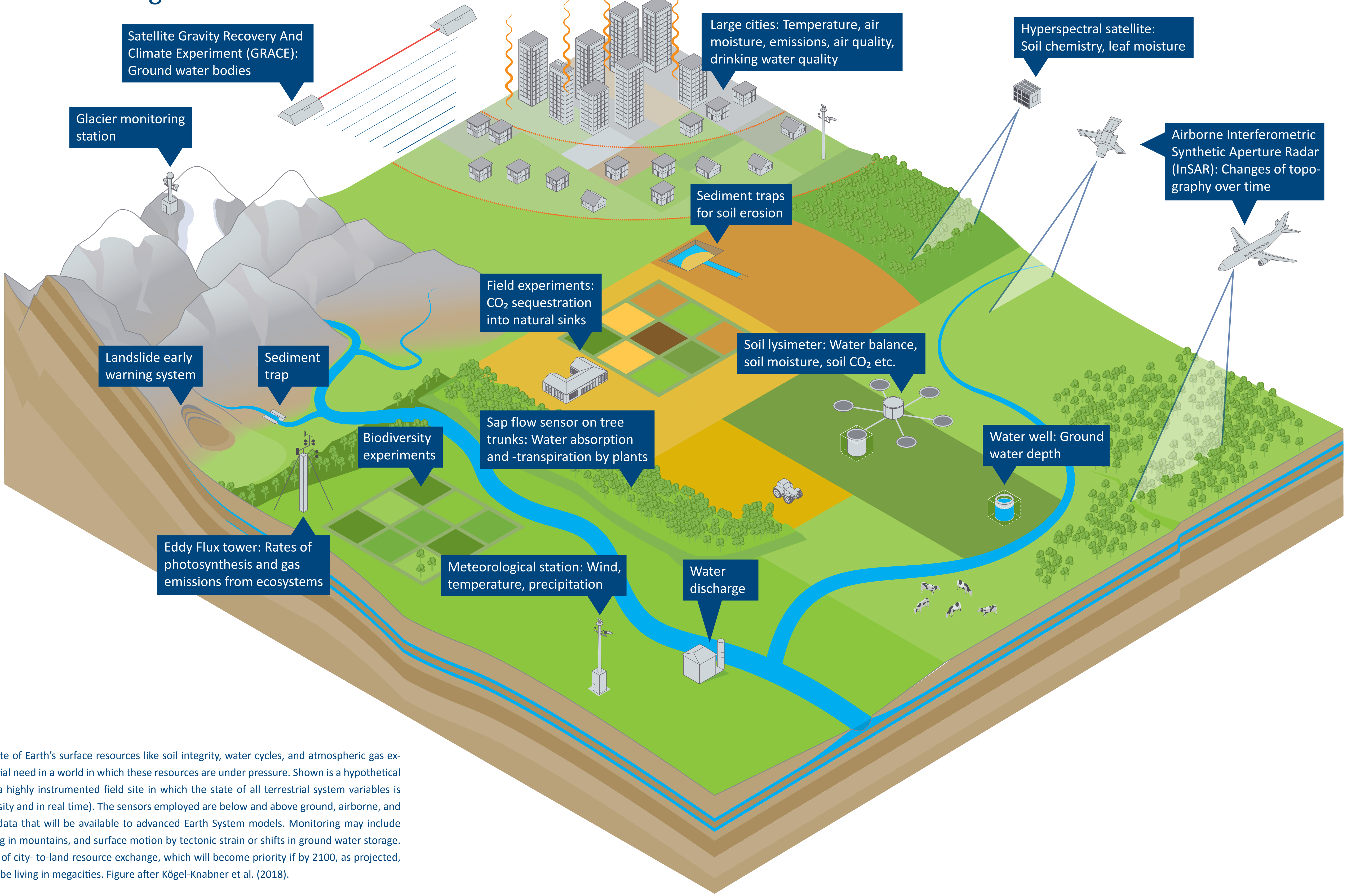


Figure 17. Monitoring the state of Earth's surface resources like soil integrity, water cycles, and atmospheric gas exchange will become an essential need in a world in which these resources are under pressure. Shown is a hypothetical "Critical Zone Observatory", a highly instrumented field site in which the state of all terrestrial system variables is monitored in high spatial density and in real time). The sensors employed are below and above ground, airborne, and satellite-based and produce data that will be available to advanced Earth System models. Monitoring may include glacial melting and land sliding in mountains, and surface motion by tectonic strain or shifts in ground water storage. Shown also is the monitoring of city- to-land resource exchange, which will become priority if by 2100, as projected, half of Earth's population will be living in megacities. Figure after Kögel-Knabner et al. (2018).

CZ science involves the operation of a global array of sophisticated field observatories that monitor the fluxes of gases, water, soil, and rock, and the involved biogeochemical conversions in real time and in the recent geologic past. The most important questions that can be addressed by CZ observatories include: 1) How is energy and matter propagation linked to porosity, fracturing, permeability, aggregation, texture, and microorganisms, and how are these patterns distributed at depth and across landscapes? 2) What is the extent, diversity, and function of the deep biosphere beneath the terrestrial surface and what sustains its metabolic functions? 3) How do CZ services, viewed from a "nature's contribution to people" (NCP) perspective (which has been suggested as a more inclusive approach stemming from, but going beyond conventional ecosystem services frameworks), evolve in response to human and natural disturbance? This question is particularly salient in urban systems and urban-rural transition zones. 4) How do CZ services respond to weather extremes, and how does climate change alter CZ processes and affect the feedbacks between climate, vegetation canopy, and bedrock over a variety of timescales? 5) How can CZ research results be used to develop strategies towards global sustainable soil use? Included in this question is the development of strategies to stop or reverse land degradation and the preservation or reinstallation of global ecosystem functioning and soil health.

What is needed?

Deep Earth and deep-sea resources

It is essential to incorporate resource and material usage into future climate and carbon models. Mineral and material sciences need to transfer expertise from fundamental research towards exploring for high-value resources in specific geologic formations. At the same time, a high level of analytical and material science expertise is required to characterise metal forms and extract metals from rock, as is the employment of large geochemical databases, remote-sensing geochemical mapping, and machine learning algorithms in the search of resources. It is important to evaluate impacts and guide extraction methods and actions to minimize their environmental impact during future exploitation. At the same time, we need to ensure that local communities will benefit and are not harmed by mining of these new metals. Engaging in a dialogue between the stakeholders needing these metals and the communities producing them is a step in the right direction. Improved geochemical fingerprinting systems will be needed to track the source and geographic origin of metals. This technology will help to secure socially responsible extraction and trade, ensuring that developing countries benefit from their economic reserves without negative impacts on their well-being, social fabric, and environment. Strict legislation is also required for minimising the ecological impact of sea floor mining, which might otherwise be seen as a convenient alternative to avoiding the socio-economic costs of land-based mining.

To use extracted materials efficiently and to develop new technologies, Earth System Science and mineralogy need to partner with material sciences. New, smart materials and – for example – pipelines that prevent diffusional loss of hydrogen during long-distance transport will be essential. Integration with the engineering sciences and cooperation with engineers will be key in this development.

Utilization of the deep subsurface for energy exploitation and storage

To exploit deep geothermal energy resources whilst mitigating the risks involved, long-term operation of subsurface experimental facilities is required and should be coupled with numeric simulations of reactive transport of fluids, including quantification of uncertainties and risk. Improved data availability and 3D models will significantly enhance understanding of the subsurface. All data should be freely available in common formats. Where facilities are located in densely populated areas, concepts need to be developed to build the public's understanding and confidence in future subsurface projects.

Use of the subsurface for energy generation, storage, and transport requires integrated research projects involving geoscientists, chemists, and engineers. A challenge will be to successfully manage subsurface risks and uncertainties based on models and that take into account societal non-technical risks identified through close collaboration between Earth System scientists, governments, and industry, and communication with the public. When developing such facilities, key decisions need to be made in full awareness of the inevitable dependencies between geological conditions, technology, and societal response.

Earth surface resources in the critical zone

Three components shall guide future water and soil research in the critical zone, viewed within an Earth System context.

Monitoring

Researching the critical zone requires building a network of global environmental and ecological observatories that use advanced sensor techniques to monitor change in real time (as proposed in detail for Germany in a report by the "Allianz der Wissenschaftsorganisationen"); their support by space-borne observation; the employment of novel "omics" technologies to target microbial functional groups and reveal new metabolic pathways for biogeochemical nutrient cycling; designing data management tools for time series observational data collected by a wide range of governmental and academic organizations; and utilizing space-based observations of the land surface.

Modelling

A new generation of regional to global hydrological models as well as vegetation and land surface models shall be developed that accurately represent rock, soil, water, air, and living organism interactions and that take into account human activities in the critical zone. These models will be informed by estimates of global freshwater fluxes and resource availability derived from monitoring data, and by patterns of natural and anthropogenic drivers. Earth observing systems must be able to monitor ecosystem feedbacks when extreme events (e.g., droughts, floods, fire, insect attacks) occur, and those data can be used to simulate crises in crop production and food supply. Humans shall be incorporated in models as agents that shape the CZ. Shallow aquifers up to a depth of 100 m will play a key role in supplying drinking water and geothermal energy. Both uses of aquifers require similar subsurface 3D modelling of geological structures, in particular detailed models of reservoir architecture in the subsurface of cities.

Managing

Novel-type analysis schemes and tools shall be developed to study complex social dynamics in response to water shortage, in tandem with state-of-the-art socio-hydrological theory development (meaning the theory that describes how humans and their actions co-evolve with hydrological systems). These measures shall be complemented with Research & Development activities aimed at increasing soil organic matter content, keeping the soil surface vegetated, applying and using nutrients such as phosphorus wisely and in a sustainable way to promote crop rotations, and using sustainable forestry methods with the aim of replacing fossil carbon and maintaining tropical forests for their ecosystem services. These approaches shall be used to assess the impact and feasibility of negative emission technologies. .

4 The Data Challenge in Earth System Science

Earth System Science produces and increasingly depends on massive data sets and numerical simulations. To effectively use them requires the development, handling, and maintenance of software frameworks that interface with gigantic, heterogeneous data volumes. While every new generation of smart technology makes life more convenient, emerging technologies are often disruptive when it comes to large data volume analysis and simulation. Without a paradigm shift in the way (digital) infrastructure is supported, Earth System Science will not be able to take advantage of the opportunities offered by the cyber realm.

4.1 Big Challenges from Big Data

With trillions of gigabytes of information generated each year by the global population, the term big data has become widely used. What is the situation in Earth Science? One characteristic of Earth Science data is their heterogeneity. Answering scientific questions often requires integration of data types generated by researchers from other disciplines. For example, understanding the history and evolution of Earth's cryosphere—key to climate studies—requires analysing data from satellite-based remote-sensing technologies, a multitude of atmospheric measurements, and ground-based or air-borne data, oftentimes collected as time series data. These data are complemented by geological observations, sophisticated laboratory analyses, and results from model simulations. The challenge is to make these data and their metadata available in internationally standardized georeferenced formats that enable interoperability and cross-disciplinary use. While there are national and international efforts to address this challenge, at the level of research groups the technical expertise and, more importantly, resources to adapt to emerging standards are mostly lacking.

Although increased monitoring of Earth's systems has led to some parts of Earth System Science to be characterised as data-rich (e.g., seismology, geodesy, weather, and climate), overall data volumes lag behind other fields such as high-energy physics and astrophysics. This situation is now changing.

1) Huge, valuable satellite-based remote-sensing data sets are increasingly made openly accessible, for example, through the European Copernicus program and its Sentinel satellites (see also USGS Earth Explorer, Google Earth engine, Chinese CASEarth). Data infrastructure in Earth System Science is not yet prepared to harvest, process, store, and analyse these data.

2) Technology has revolutionized the way in which global Earth System observables are monitored, such as continental water cycles, slope stability in mountain ranges, land use and vegetation change, or in hazardous regions such as near active volcanoes and potentially dangerous seismogenic faults. Cheap, wire-free, and plen-

tiful sensors (Large N networks), as well as entirely new sensing technologies (e. g., strain measurements using public fibre-optic communication cables) are now widely employed. Similarly, in the future swarm-based drone monitoring technology will provide huge amounts of very high-resolution image data. These technologies provide increasingly higher spatial and temporal resolution but also generate data volumes that are orders of magnitude larger than what has previously been available. Yet, there is no single site where all these global and regional observational data are collected, harmonised, made interoperable, and available globally.

3) In geomicrobiology, for example, genomic tools are producing unprecedented amounts of sequencing data from modern and sedimentary materials whose storage, reproducibility, and longevity are not supported by interchangeable standards.

4) The public is collecting more and more data (e.g., accelerometers in mobile phones). These "citizen science" data, coming from millions of sensors, provide researchers with real-time information that is highly relevant to natural hazard early warning systems and a potential management response.

5) Earth scientists have collected huge amounts of analogue data from all kinds of geological archives in the past and are continuing to assemble such data. To make this invaluable data accessible for the scientific communities in digital format is mandatory, both for the exchange of existing knowledge and testing of hypotheses, as well as for developing a deeper understanding of the links between system behaviour across timescales, from the instrumentally resolved timescale to the long-term geological timescale.

Big data in Earth System Science thus present tremendous challenges for subsequent processing and model-building. Data archives must be established physically adjacent to CPU-rich infrastructure (high-performance computing centres), supporting the concept of long-term domain-specific computing infrastructure and enabling efficient hypothesis testing combining big data with the required compute power.

4.2 Data Infrastructure — Making Big Data available

When using raw, unprocessed data, the processing steps need to be encoded so that subsequent results are fully reproducible. When using secondary products derived from complex workflows, the provenance of data must be documented, stored and made available in a consistent way to assure quality control and uncertainty quantification for any subsequent modelling and hypothesis building. The scientific community has not yet adequately addressed either issue. Common formats and standards are needed to allow clear identification of the sources of uncertainties along the entire scientific workflow and to provide for scientifically sound data replication.

Should there be unique access points to all georeferenced Earth System data? Let us imagine a data portal that provides access to deep-time and real-time original raw and time-series data (e.g., ground motions, temperature, rain, geological data) and derived, secondary products (e.g., land use, soil conditions, crustal deformation) for all levels of expertise (from scientists to the public). Such an Earth System Science Data Portal would undoubtedly be a powerful enabler for all fields of Earth Sciences, preparing for hazard, and risk forecasting. It would be consistent with the open-data, open-source philosophy that underpins national and European funding for research data initiatives such as NFDI4Earth[8] and EPOS. Companies such as Google (earth engine, currently focusing on satellite data) pave the way and demonstrate that the technologies to achieve this goal are available. It is important to note, however, that building such digital Earth infrastructure–including a geo-cloud system such as Gaia-X–requires sustained investments like large research facilities in Physics, Astronomy and Ocean Sciences.

4.3 Machine Learning — Opportunities for Noisy Data and Unknown Relations

Large Earth System data sets require automated analysis strategies. In many cases, there is a physical understanding (or model) that relates the input of potentially noisy and uncertain data to the desired output. Classic examples are the automated evaluation of the origin time, the location, and the magnitude of globally observed earthquakes, or the forecasting of a hurricane track based on assimilated data and fluid dynamic models of the atmosphere. In these cases, state-of-the art statistical models can provide the essential quantitative assessment of uncertainties.

In cases where large, complex data sets need to be analysed and interpreted without quantitative models relating input and output, machine learning (ML) tools, particularly deep learning, come into play. If sufficient previous real (or synthetic) combinations of input and output parameters are available for training an ML algorithm, an instant answer to complex pattern recognition problems is possible. This will be increasingly important in situations such as in early warning, when rapid analysis and response is essential. In addition, ML algorithms have been shown to outperform more classic approaches in de-noising data when noise levels are high.

If Earth System data integration succeeds, further opportunities may come from artificial intelligence (AI) tools that are being increasingly developed in the big data community. Automated analysis of very large data sets may reveal hidden correlations, structure, and connections between observables that so far have been overlooked. The challenge for Earth System Science is to embrace these evolving technologies where useful, requiring tighter-than-before cooperation with the corresponding domains of mathematics and computer science.

4.4 Digital Twins of the Earth

Digital Twins are fine-grained virtualizations of physical objects and systems. They have been widely applied in the engineering realm for tasks such as engine optimization and port management. Employed in Earth System Science, Digital Twins will enable the production of scenarios for future states and changes of the Earth system, and the assessment of the potential results and risks of proposed actions, and will offer options for sustainable pathways (Fig. 18). As a concept, digital twinning is gaining momentum in Earth science, particularly as a way to intuitively bundle and provide easy access to environmental data, models, and simulations. A well-constructed digital twin of Earth

---

[8] https://www.nfdi.de

will enable a wider range of users to interact with digital assets to explore current and future scenarios, especially related to human interactions with the Earth System. The development of a Digital Twin of the Earth Framework goes beyond the capacity of one nation and requires international engagement and commensurate resources. The benefit will be substantial, as it will allow users to create a family of application-focused digital twins that collectively have access to a range of Earth System data, predictive systems, and forecasting. As more digital twins emerge across Earth's digital ecosystem, it is imperative that we build a framework to secure interoperability between them. In addition, the massive production of numerical data and their handling and storage is a challenge that only an international effort will be able to address. Through this Digital Twins framework, forecasting and predictive capacities can be more rapidly rallied to support science-based decision-making through the exploration of scientifically grounded "what if" scenarios.

Concept of digital twins of the Earth system

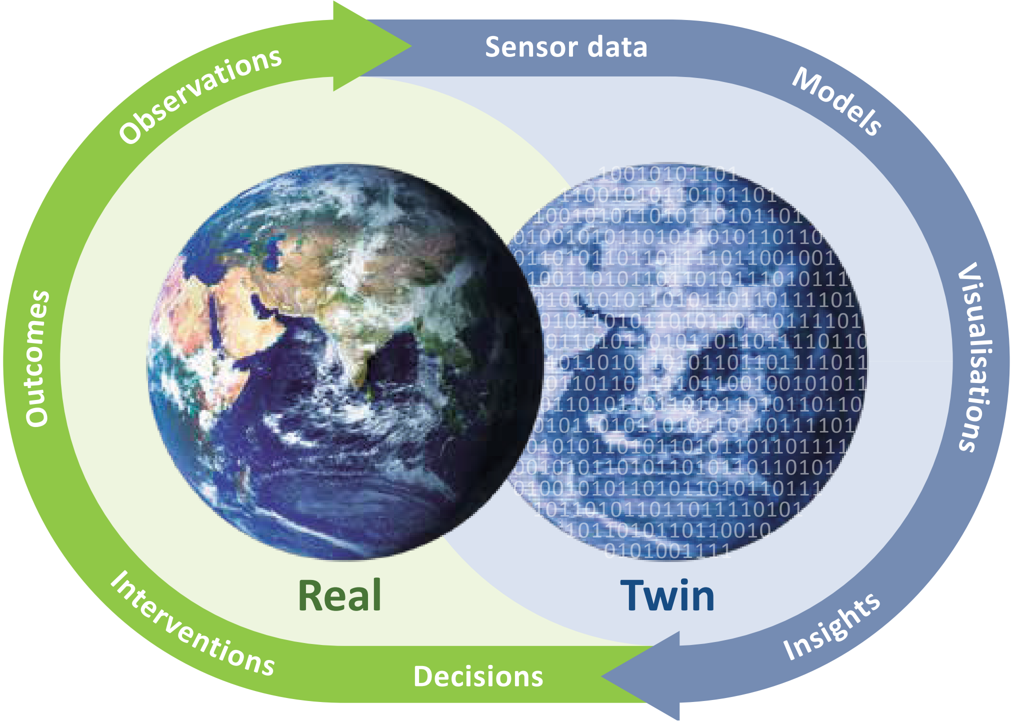


Figure 18. Concept of Digital Twins of the Earth System. A digital Earth System twin is a virtual model that accurately represents the real Earth System. The subsystem under study – for example, the Earth surface system – is equipped with various sensors that relate to key feedback parameters. These sensors provide data on various aspects of the subsystem's functioning, such as matter and energy cycling, climate-biosphere-geosphere feedbacks and more. The data are then passed to a processing system and applied to the digital copy. Once such data are available, the virtual model can be used for simulations, investigating interactions, defining thresholds, and working out possible trajectories. The goal of such models is gaining valuable insights that can then be applied back to the original physical object for the purpose of developing and deciding on possible solutions.

4.5 Mastering Computers of the Future – to Scale or not to Scale

The data world is parallel. While high-end computational facilities have operated with parallel processing systems for decades, today even smartphones, laptops, and PCs are based on multi-processor hardware. What are the consequences for Earth System Science, where progress depends to a significant extent on sophisticated process simulation software that is running and scaling well on the latest generation supercomputing systems? They are manifold, challenging in many respects, requiring a paradigm shift in the way Earth System Science is conducted in the future.

Island solutions for computational problems developed by individual research groups are in many cases no longer an efficient option. The rapid evolution of computational hardware (e.g., clusters of gpu and cpu processors) has an important implication. Community software solutions professionally developed and maintained in cooperation with computational scientists are the only way to sustain software solutions that would enable cutting-edge research. Earth System simulation problems will provide ample work for the largest supercomputers, thanks to the high spatial resolution that is required even to approximately model the realistic behaviour of atmospheric processes, flow processes in Earth's interior, or the generation of Earth's magnetic field, not even considering the quantification of associated uncertainties.

Today, we need to join forces at national and international levels to fill the gap between theory, models, and observations providing Earth System Science with the corresponding compute engine that matches the gigantic observational infrastructure that is expanding at high rates. To foster efficient interdisciplinary research in Earth System Science case we need to actively engage in the development of so-called "Digital Twins" that aim at integrated modelling solutions of the heavily interconnected physico-chemical subsystems of our planet (Fig. 19). As is the case for the Earth System data services, sustaining the simulation and data processing capabilities is a tremendous task, requiring a new generation of IT-literate Earth System scientists capable of operating at the interface between computational science and Earth System science. Research institutions and universities must adapt to provide education and training as well as attractive career paths for this new breed of Earth System scientists.

4.6 What is needed

- Support community efforts to collect sustainable Earth science data, develop data products (as envisaged in the Nationale Forschungsdateninfrastruktur NFDI4Earth, the European EPOS initiative and the European Open Science Cloud EOSC), unify metadata standards, and enable transdisciplinary data exchange.

- Develop long-term strategies to build the required digital infrastructures that will offer Earth System science communities open and easy access to real-time and archived georeferenced observational time-series data of our planet including linked geo-cloud systems.

- Train a new generation of scientists to operate at the interface between Earth System Science and computational/data science, providing them with appropriate career opportunities at academic levels in universities; develop novel structured training programs at all levels that bridge to computational science and mathematics.

- Foster the development of computational Earth System models (digital twin of Earth) that capture the complexity of natural processes and the interactions between the solid Earth and Earth's changing surface, biosphere, atmosphere, ocean, and the anthroposphere.

- Develop a long-term strategy for Earth System Science domain-specific data and high-performance computing centres, co-designing large-volume observational data access and extreme-scale simulation tasks.

5 Academic Education for Earth System Research: Challenges and Future Needs

At present in Germany, university curricula which address topics related to the Earth do not offer a clearly identifiable training program with overarching perspectives on the whole Earth system. This not only limits development in the understanding of the Earth system, but also hinders the recruitment of younger generations—who are particularly concerned with the future habitability of our planet—into geoscience degree programs. Nevertheless, approaches which centre the study of the Earth from an Earth systems science perspective offer the means to address these challenges, namely through 1) the development of new Earth System Science curricula, and 2) the addition of Earth system modules to existing courses. These curricula will both convey the fascination of a science as driven by human curiosity and empower students to contribute to solutions for pressing future issues in a changing job market.

5.1 The Multitude of Geosciences Degree Programs

Many young people today recognize that the earth is undergoing dramatic change. They are deeply concerned about the future of our planet, which significantly affects their future and that of their children. Many are politically engaged. The academic system in Germany should therefore offer this generation the tools to manage the processes necessary for the preservation of a habitable Earth based on scientifically proven principles.

However, such a clearly recognisable curriculum does not exist in Germany at the moment. The curricula in the Geosciences range from the individual sciences of the solid earth and the planetary system (Geology, Mineralogy, Geo- and Cosmochemistry, Palaeontology, Geophysics) to the sciences of the earth's surface (PhysicalGeography, Soil Sciences, Geoecology, Hydrology, and Environmental Sciences), Oceanography, the sciences of the atmosphere and the cryosphere (Meteorology, Glaciology; often located as subdisciplines of Physics) to disciplines concerned with surveying and mapping our planet (Geodesy and Remote Sensing, Geoinformatics), and Human Geography.

The corresponding degrees reflect this fragmentation, although there has been progress over the past two decades. For example, a unified geoscience curriculum has now been created at most campuses, combining primarily the "solid earth" subdisciplines: Geology, Mineralogy, Geo- and Cosmochemistry, Palaeontology, Geophysics, and the respective applied fields. However, an increasing number of specialized degree programs often straddle the traditional boundaries of the disciplines. Degrees in "Climate Systems Science" or "Earth Systems Science," which might be of interest to the generation concerned, are still few and far between. Although the geosciences have much to offer that is relevant to many students' concerns about the future of our planet, they typically opt for university degrees in, for example, Physics, Mathematics, or Chemistry, or they select degree programs in the environmental domain.

Given the enormous tasks posed by climate change, the management and sustainable use of natural resources that the Earth and its biosphere offer us, and the urgent need for solutions in all areas of applied geoscience, the pressure to develop new courses and integrate new fields will increase.

For such innovative educational concepts, the scientific concepts and new technological possibilities of Earth System Science offer an excellent guiding principle.

5.2 Teaching Earth System Science

The complexity and interconnectedness of all parts of the Earth system and their dynamic feedbacks have been described many times in this report. Yet at universities, isolated aspects of Earth system science are often taught only within their respective subdisciplines. Given the current and future challenges, we need a broader view of university education. The goal is to train the next generation of competent Earth system scientists capable of addressing new and exciting research questions about the origins of our planet and the evolution of life on it, as well as addressing the pressing societal, economic, and technological needs of a changing world.

Education in Earth System Science could thus include the following elements:

1) The teaching of Earth System Science provides students with a fundamental understanding of how our planet came to be, how it functions and enables life, and the natural resources required for the development of post-industrial societies. The course deepens students' abilities to develop and apply new analytical and monitoring tools for Earth observation. This can be achieved through hands-on collection and interpretation of real data, or it can train more practically oriented professionals to solve specific problems in the applied sector.

2) Earth system scientists should be empowered to handle large data sets that they can analyse and evaluate, including machine learning methods. This so-called "data literacy" will prepare them for modern research and a variety of career opportunities beyond the traditional geosciences.

3) The focus of modern Earth System Science is the nature of Earth as a system. Hence, new curricula should also include the broader concepts of systems science and the non-linear behaviour of complex, often chaotic systems.

4) The teaching of Earth System Science should embrace new teaching methods, including virtual learning environments, which have been shown to have a positive impact on student learning.

5) Future scientists need to be empowered to communicate scientific findings. This will enable them to competently inform relevant actors, decision-makers, and the public. This ability is essential for communicating and preparing society for the consequences of likely environmental changes in the Anthropocene, for formulating measures to adapt to climate change, and for providing policy advice related to the impacts of a changing world.

6) Because of its importance for our future, Earth System Science should already be an integral part of secondary school curricula. The goal is both to achieve a well-informed society prepared for the coming transformations and to attract the next generation of students and researchers to the field.

The new framework for Earth System Science curricula as outlined here will inevitably face tensions between the existing course structures and the need to include the "broader context" in education at an early stage. The new academic training programs to be developed can therefore either follow on from the basic training in the existing Earth science disciplines, preserving the specialty competencies of the disciplines, or alternatively, the programs could provide the basis for later specialization and in-depth study in the specialized geoscience disciplines using an Earth System Science curriculum.

The following explains these approaches and elaborates on individual aspects.

5.3 Strengthen the Link between the Geosciences and the Natural Sciences

We encourage the establishment of a discipline that is clearly assigned to the natural sciences and that combines the basic elements of geosciences with those of the other natural sciences. This is already the case in many geoscience departments in other parts of the world. The fundamental concepts of the natural sciences form the foundation of Earth system research and education, and they will become increasingly relevant to all applied and solution-oriented fields of the geosciences.

A particular challenge will be to attract a previously neglected group of students with a special interest in basic science and mathematics to the emerging field of Earth systems research. Such students enrol, for example, in prominent basic subjects such as Astrophysics, Cosmology, Molecular Biology, or Solid-state Chemistry. Earth system science, with its equally large fundamental questions such as the origin of planets and life, should be equally as fascinating for this target group.

Thus, such a new course offering in the context of Earth System Science should be attractive to students interested in basic research, but equally to those seeking employment in environmental monitoring, planning, and management ("diagnosing" problems). Those who will work in applied fields such as Environmental Geology, Geotechnology, Materials Science, and Economic Geology would also benefit from the broadened scope of instruction because the Earth System Science curriculum will have strong connections to other disciplines such as Human Geography, Geoecology, and Geoinformatics.

The focus of a modern Earth System Science curriculum is the interconnected nature of the Earth system, which has been detailed in this report. Therefore, new courses should incorporate the broader concepts of systems science and the non-linear behaviour of complex, often chaotic systems.

5.4 Using New Technologies

Advances in the Geosciences have always relied on the introduction of new observational and analytical tools. Modern Earth System Science and its applications require additional skills in, for example, data science and the handling of high-resolution sensor data from satellite observations of Earth surface processes that provide real-time analyses of air, water, ocean, soil, groundwater, and more. For many of these analyses, the most advanced analytical instruments are used for trace element and isotope and solid-state analysis down to the nanometre scale. These measurements allow for the reconstruction of the evolution of the planet's interior and its crust at the Earth's surface as well as its modern biogeochemical and oceanic cycles and past climatic states. Powerful methods of inorganic and organic geochemical analysis and molecular biological methods are essential tools in environmental monitoring and Environmental Geochemistry; geophysical methods and the associated numerical evaluation procedures are the same for probing the near-surface and deep subsurface; experimental and synthesis techniques of materials research are also part of the toolkit. Numerical simulations based on mathematical models are used to model the interactions among Earth system components, including humans.

Compared to other scientific disciplines, competency in handling and analysing large complex data sets ("data literacy") in Earth System Science involves three characteristics: 1) data from Earth system science commonly exist in a unique spatial context, 2) they often relate to direct observations, physical samples, or model results, and 3) they increasingly occur in exceptionally large data sets (i. e., individual data sets often exceed several terabytes in the ten-digit range). Data related to human interaction with Earth's resources also often exhibit these three characteristics. Given the rapidly increasing volumes of Earth observation data in all domains, the introduction of basic and advanced academic training in research data management and analysis is essential. "Data literacy" will enable future geoscientists to exploit the full potential and abundance of growing data sets. Even future teaching will incorporate new methods of data visualization, including fully immersive virtual reality methods in the classroom.

These complex methods and a firm understanding of the fundamental importance of quantitative analytical data tools require solid foundational knowledge in mathematics, statistics, physics, chemistry, biology, and data and computer science. Therefore, university education in all Earth science curricula needs to place a greater emphasis on STEM science (science, technology, engineering, and math) and consider information technology and data literacy to be at the intersection of Earth system and data science. Ideally, both should be taught at the undergraduate level.

5.5 Communicating Solutions

Researchers in Earth system science should perceive the relevance of their forward-looking scenarios on the conditions of life on Earth and their potential consequences for human economic and social behaviour and mobility. They need to monitor, describe, and predict the depletion of natural resources and the degradation of ecosystem services, as well as determine how fast the Earth is approaching critical thresholds. Earth system science will have to consider the societal and political dimensions of such changes and pressures.

Even more important are the implications for communication to and with society. Effective communication of research results and their potential impacts to relevant stakeholders in politics, industry, and the public is crucial for opinion formation and public acceptance of necessary measures such as those involving climate change mitigation and adaptation. To ensure such knowledge transfer occurs, scientists not only need excellent communication skills, but they also need to consider the psychological context of their research and the potential consequences of research findings. Future students of Earth system science should learn appropriate skills. Linking scientific findings, policy decisions, executive actions, and public awareness and acceptance will be critical in the future.

5.6 Starting in Schools

Lessons addressing these interdisciplinary relationships should begin in schools. But even within school curricula, no explicit school subject exists with “the Earth” at its core. Elements of Earth System Science are taught under the umbrella of Natural Sciences: within Physics, Chemistry, and Biology. But often these lessons occur in isolation and without explanation of the broader connections between disciplines. In the future, students must be able to perceive their role in ensuring our Earth remains a habitable planet. Societal, commercial, and human activities should likewise be connected to the aspects of the Earth system as described here. Researchers at both universities and research institutes should be encouraged to provide school teaching staff with quality educational materials and to influence the development of school curricula. Educational curricula should spark an interest in Earth system science in order to produce a steady stream of qualified students and researchers who will be capable of addressing future challenges.

5.7 What is needed?

We present two options for introducing Earth System Science: 1) developing new Earth System Science courses starting at the undergraduate level; and 2) adding Earth System Science modules to existing courses. Option 1 suggests teaching the big picture and systems thinking from the beginning. Option 2 emphasizes preserving the identity and conceptual and methodological strengths of traditional disciplines.

In particular, for option 2, it will be critical to offer introductory and integrated Earth System Science courses at the undergraduate level for all students majoring in Geography, Earth Science, and Geoecology, as well as Physics, Biology, and Chemistry, or Agricultural Science. Earth System Science should also be offered as a minor to students majoring in economics and social sciences.

Option 1, a bachelor’s degree in Earth System Science should allow future students to acquire a solid foundation in Physics, Mathematics, Biology, Chemistry, Statistics, and Data Science combined with a basic knowledge of Geoscience, Natural Resources, Climate Science, Soil Science, and Ecology. Graduates can then pursue either a master’s degree in Earth System Science or choose between Master’s programs in the “traditional geosciences”, Geography, Engineering Geology, Economic Geology, Environmental Science, and applied economics and social sciences. At the master’s level, additional bachelor’s degree graduates in the other natural sciences must be attracted to careers in Earth System Science.

To meet the diversity of the new educational requirements, universities may offer master's degrees in Earth system science with in-depth training in one of three directions: 1) in the STEM disciplines (Science, Technology, Engineering, and Mathematics); 2) in Data Science; 3) in communication, social, psychological, political, and social sciences. Given the challenge of integrating Earth System Science into existing curricula, consideration should be given to extending the curriculum length beyond 10 semesters (bachelor's plus master's).

6 Recommendations

Given our planet's current trajectory and the urgent need to understand and address the consequences of human actions, it is time to embrace Earth System Science as the overarching framework of all Geoscience disciplines in Germany. To this end, this report identifies three connected pursuits as leitmotifs: (i) **discovery** science based on curiosity and the generation of knowledge about our planet; (ii) **diagnosis** of the state and a planet that is changing due to increasing human pressure and defining limits of safe conditions for human civilizations and habitability; (iii) finding and communicating **solutions** to some of the major challenges that humankind faces. With Earth System Science as the overarching framework, Geosciences in Germany will become more inter- and transdisciplinary, more quantitative, and more digital.

Decision makers from university, Geoscience units, research centres, funding organisations, private sector partners, the Geoscience community and the scientific Geo-societies should embark on a discourse to develop a set of actions that address the following report recommendations.

6.1 Recommendations for Decision-Makers

Shape Organisational Units to Enable Earth System Science Synergies

To empower the individual German Geoscience institutions to meet the new challenges, they need to develop an optimal balance between interdisciplinarity and maintaining specialty expertise. To this end, strategy discussions, comparison with international best practice analysis, profile building, and the identification of optimal organisational formats are needed to pave the way towards the development of innovative and scientifically competitive institutions. Incentive measures are the best vehicle for fostering cross-disciplinary idea development (with many funding schemes available by DFG and other organisations in Germany), and Earth System scientists should make use of these funding options.

Build Capacity in Earth Observation and Analytics

Monitoring changes in the Earth System in real time with high spatial coverage and resolution requires both massive investment in and long-term financial commitment to Earth observation systems, whilst supporting state-of-the-art analytical tools to determine the properties, pathways, and mass fluxes of Earth materials. German Ocean Science serves as an example of world-class quality in observation capacity that needs continuous support. We call for establishing similar capacity in terrestrial observation systems, geophysical infrastructure and rock laboratories, hydrological monitoring, and airborne observation of land cover and atmospheric properties. Observatories should not be restricted to locations in Germany. They should be based in global areas most affected by climate change or suited to probing Earth's subsystems that most strongly impact our livelihood. We recommend that funders, universities, and research organisations in Earth System Science jointly design a national roadmap for large Earth observation infrastructure. To make best use of such observatories, and to leverage hypothesis-driving science programs, observation and analytical capacities operated by non-University institutions (e.g., Helmholtz, Max Planck, Leibniz Associations) should be designed jointly with university partners and the DFG senate committee for the Earth System Sciences (SKE).

Invest in digital infrastructure for Earth Data Sciences, Models, and Computational Capacities

Without a paradigm shift in the way (digital) infrastructure is supported in Germany, Earth System Science will not be able to take advantage of the opportunities offered by the cyber realm nor exploit the rapid growth of data, including the ability to explore future Earth trajectories via a digital twin of Earth. A national strategy is needed for the sustained development, funding, and dissemination of digital infrastructure at all levels, from basic support at individual institutions to large-scale initiatives that encompass several institutions, beyond the NFDI4 Earth initiative. The strategy should include the infrastructure and support for community efforts to develop interoperable data formats, accessible data products, and realistic simulations, as well as provide all public stakeholders with open access to all data. To implement this strategy, and to allow German geodata sciences to maintain independence from commercial providers (like the Google Earth Engine), requires investment of the order of 10^8 EUR for setup and long-term maintenance of a national Geodata and computing infrastructure.

Enable new private sector job opportunities by technology transfer

The Earth System Science activities in monitoring change and suggesting solutions provide new opportunities for transfer of scientific knowledge into the private sector. Start-ups and consultancies will add employment opportunities to the traditional geo job market in new business fields. Potential fields are in Geodata management and analytics, designing models and tools for assessing the vulnerability of public and private infrastructures, developing, implementing, and marketing negative emission technologies within a market driven by emission certificate trading, utilisation concepts for mineral resources and geothermal energy, sensor development and deployment. Research institutes and Universities are encouraged to play a role in this development by consulting and financial support for founding spin-offs.

Integrate into the European Research Area for Expanding Scale and Scope

Germany cannot pursue these tasks alone. The European Research Area provides an excellent environment for Earth System Science. Current examples include, but are not limited to, the programs EPOS (European Plate Observing System), ESFRI (European Strategy Forum on Research Infrastructures), LIFE (EU Programme for the Environment and Climate Action), the EU 10-year “Destination Earth”-initiative that will involve creating a digital twin of Earth to map climate development, the European Open Science Cloud (EOSC), and European institutions like the European Space Agency (ESA), or the European Southern Observatory (ESO). Significant financial, institutional, and human investment are imperative to empower Earth Sciences in Germany, to remain competitive, and to significantly contribute to these large and EU initiatives.

Encourage Curiosity and Interest in Earth System Science in Schools

To nurture the next cohorts of undergraduates and researchers in Earth System Science, its concepts in secondary and high school will need to become highly relevant teaching topics. To enable future training in these topics, it will be important to involve school educators to include Earth System Science concepts in teaching, and to do so, their school teaching curricula will need to be updated. Earth System Science content cannot remain limited to any specific subject: students can be exposed to it in Geography, Chemistry, Physics, Biology, Mathematics, and even Economics, and Social Science.

6.2 Recommendations for the Geoscience Community

Train the Next Generation of Earth scientists

The strengthening of Earth System competencies, the energy transition, stricter environmental and legal regulations, and Big Data applications require development of new curricula content. In addition to ensuring student IT/data literacy, universities will need to strengthen the interface between Earth System Science and Computational Science and place greater emphasis on STEM sciences. As a main goal, undergraduates need to be enabled to "think" Earth System Science, while having strong disciplinary skills. To achieve this goal, there are several options for the curriculum structure:

(i) Given appropriate resources and scientific diversity at a large Earth Science department, a full BSc-MSc curriculum in Earth System Science could be offered as an option in addition to existing master's degrees in the "traditional" Geo-curricula (Geosciences, Geography, Engineering and Applied Geology or Economic Geology).

(ii) Alternatively, an Earth System Science master course could be developed as an option following a degree in any of the existing Geoscience BSc curricula.

Any Earth System Science curriculum should be open and flexible to accept graduates from Physics, Chemistry, Biology, Data Science and any other natural sciences at the BSc level.

Given the challenge to integrate Earth System Science into new curricula, an extension of curriculum duration beyond 10 semesters (BSc and MSc) should be considered.

Interface to other Disciplines

Developing the capacity for two-way communication of solutions goes beyond what the Geosciences alone can achieve. This activity can be carried out in collaboration with the behavioural/psychological sciences (with respect to humans' perception of change), the economic sciences (with respect to the implementation of economic steering tools like a carbon price), moral philosophy (with regards to the development of norms in a world where local activities result in global implications), and the sociological and political sciences (with respect to the development of political measures). Maintaining public awareness for the significance of scientific discovery and related efforts for mitigation of and adaptation to risks hinges on successful two-way communication. In this context, the UN Sustainable Development Goals provide an excellent framework for guiding Geoscientists in the responsible use of Earth resources without compromising the needs of future generations.

Develop Cross-Disciplinary, Large-Scale Initiatives

The recent success of the climate and marine sciences in advancing research through integrated, cross-disciplinary collaboration towards the grand challenges facing us is a wake-up call for the Earth Sciences community as a whole. These and international overarching cross-disciplinary programs in the Earth Sciences (such as the International Ocean and Continental Scientific Drilling Programs, IODP and ICDP), as well as similar successful large programs in other natural sciences are prominent examples. Such programs will help the science community to address the first-order research goals even if their organizational unit size is below the limit that allows to address these goals alone. The scale of the arising planetary challenges requires using an Earth System Science framework to advance a new generation of overarching initiatives that will also serve to preserve international competitiveness of German Geoscience.

Empower the Academic Geoscience Societies to be Leaders in this Transformation

Scientific societies are encouraged to play a key role in the empowerment of Earth System Science. They are the only entities whose membership includes scholars from universities and research centres, private sector practitioners, and undergraduates. Currently, more than 25 individual Geoscience societies exist, a situation Earth System Science cannot afford to maintain. Smaller societies should consider consolidating and merging to realize the transformation. As integration occurs, scientific societies may form individual scientific divisions that maintain their disciplinary specialities within an overarching framework. Thus, individual disciplines can maintain their identity and allow for interdisciplinarity and transdisciplinary expansion, nevertheless. Speaking with ‘one voice’ will be crucial for the Earth Sciences, both in communicating with the public as well with decision-makers and funders.

References and further reading

acatech – German Academy of Science and Engineering; German National Academy of Sciences Leopoldina; Union of the German Academies of Sciences and Humanities (2018) Raw materials for the energy transition. Berlin. Link: https://energiesysteme-zukunft.de/fileadmin/user_upload/Publikationen/PDFs/ESYS_Position_Paper_Raw_materials.pdf

Australian Academy of Sciences (2018) Our Planet, Australia's Future – A decade of transition in Geoscience. Link: https://www.science.org.au/supporting-science/science-policy-and-sector-analysis/decadal-plans-science/australian-geoscience

Daniell JE, Khazai B, Wenzel F & Vervaeck A (2011) The CATDAT damaging earthquakes database, National Hazards Earth System Science 11: 2235-2251,

Dachverband der Geowissenschaften (DVGeo), Wissenschaften in der Schule. www.geowissenschaften-unterrichtsmaterial.de

Fuller R, Landrigan PJ, Balakrishnan K, Bathan G, Bose-O'Reilly S, M et al. (2022) Pollution and health: a progress update. The Lancet 6: e535-e547.

IGBP (1986). International Geosphere Biosphere Program. Link: http://www.igbp.net/

IGBP (2015) Link: http://www.igbp.net/news/pressreleases/pressreleases/planetarydashboardshows-greataccelerationinhumanactivitysince1950.5.950c2fa1495db7081eb42.html

IPCC (2019) Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC). Intergovernmental Panel on Climate Change, Genf. Link: https://www.ipcc.ch/srocc/

IPCC (2022) 6. Assessment Report, Working group 3. Geneve.

National Academies of Sciences, Engineering, and Medicine. 2020. A Vision for NSF Earth Sciences 2020-2030: Earth in Time. Washington, DC: The National Academies Press. doi: 10.17226/25761.

Kögel-Knabner I, Teutsch G, Adrian R, von Blanckenburg F, Flügge UI, Kolle O; Kleinn C, Küsel K, Lischeid G, Löw A, Schäfers C, Schmid HP, Simmer C, Vereecken H, Walz R (2018) Empfehlung zur Einrichtung eines nationalen Observatorien-Netzes für die terrestrische Ökosystemforschung. Abschlussbericht der Arbeitsgruppe "Infrastrukturen in der terrestrischen Forschung" der Allianz der Wissenschaftsorganisationen. Link: Abschlussbericht der Allianz-Arbeitsgruppe "Infrastrukturen in der terrestrischen Forschung"

Lenton T (2016) Earth System Science – a very short Introduction. Oxford University Press, Oxford.

Ludden J (2020) Where is geoscience going? Geological Society, London, Special Publications 499: 69-77. Link: https://doi.org/10.1144/SP499-2019-212

Lüthi D, Le Floch M, Bereiter B, Blunier T, Barnola JM, Siegenthaler U, Raynaud D, Jouzel J, Fischer H, Kawamura K & Stocker TF (2008) High-resolution carbon dioxide concentration record 650,000–800,000 years before present. Nature 453: 379–382.

Meehl, G. A., Senior, C. A., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R. J., Taylor, K. E., and Schlund, M., 2020, Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models: Science Advances, v. 6, p. eaba1981.

Merschel P, Wolf-Brozio U, Kucera M & Eicker A (2020) Herausforderungen der universitären Ausbildung im Bereich der Erdsystemwissenschaften in Deutschland. GMIT 80 20. Juni 2020.

NASA (1986) NASA Advisory Council. Earth System Sciences Committee, Earth system science overview: a program for global change, Publisher: National Aeronautics and Space Administration, Washington.

National Committee for Earth Sciences (2018). Our Planet, Australia's Future: A decadal plan for Australian geoscience 2018–27 (Australian Academy of Science).

Plag HP, Blocklebank S, Brosnan D, Campus P, Cloetingh S., Jules-Plag S. & Stein S (2015). Extreme Geohazards: Reducing the Disaster Risk and Increasing Resilience. European Science Foundation.

Raup DM, Sepkoski JJ (1982) Mass extinctions in the marine fossil record. Science, 215 4539: 1501-1503.

Scheffer M, Bascompte J, Brock WA, Brovkin V, Carpenter SR, Dakos V, Held H, van Nes EH, Rietkerk M & Sugihara G (2009), Early-warning signals for critical transition, Nature Reviews. https://doi.org/10.1038/nature08227

Schellnhuber HJ, Rahmstorf S & Winkelmann R (2016) Why the right climate target was agreed in Paris. Nature Climate Change 6: 649–653.Steffen W, Richardson K, Rockström J, Cornell SE, et.al. (2015). Planetary boundaries: Guiding human development on a changing planet. Science 347: 736.

Steffen W, Richardson, Rockström J et al. (2020) The emergence and evolution of Earth System Science. *Nature Reviews Earth & Environment* 1.1 (2020): 54-63.

Uhlig D & von Blanckenburg F (2019) How Slow Rock Weathering Balances Nutrient Loss During Fast Forest Floor Turnover in Montane, Temperate Forest Ecosystems. Frontiers in Earths Science 7: 159. Link: https://doi.org/10.3389/feart.2019.00159

United Nations (2015) Transforming our world: the 2030 Agenda for Sustainable Development. United Nations: New York, NY, USA.

Westerhold T, Marwan N, Drury AJ, Liebrand D, Agnini C, Anagnostou E, Barnet JSK, Bohaty SM, De Vleeschouwer D, Florindo F, Frederichs T, Hodell DA, Holbourn A, Kroon D, Lauretano V, Littler K, Lourens, LJ, Lyle MW et al. (2020): An astronomically dated record of Earth's climate and its predictability over the last 66 million years. Science 369: 1383-1387.

The World Bank (2020) Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. Washington D.C. Link: https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Clima-te-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf (abgerufen am 12.01.2022).

WBGU (2011) Flagship Report of the German Advisory Council on Global Change “World in Transition – A Social Contract for Sustainability”, Berlin.

Wefer G (2010) Dynamische Erde - Zukunftsaufgaben der Geowissenschaften: Strategieschrift Ed.: Wefer G. Bremen: Senatskommission für geowissenschaftliche Gemeinschaftsforschung der Deutschen Forschungsgemeinschaft 2010. 367 p., Bonn.

Wiedermann M, Winkelmann R, Donges JF, Eder C, Heitzig J, Katsanidou A, Smith EK (2019). Domino Effects in the Earth System--The potential role of wanted tipping points. arXiv preprint arXiv:1911.10063.

Wysession M et al. (2010) Earth Science Literacy Initiative, US National Science Foundation, Arlington. Link: http://www.earthscienceliteracy.org/document.html

UNO, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. United Nations.

Persons involved

The members of the working group participated in the statement on a voluntary basis. The working group was established in May 2017 and was constituted in December 2017.

Editorial board

Prof. Dr. Friedhelm von Blanckenburg ML	Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum
Prof. Dr. Onno Oncken ML	Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum
Prof. Dr. Gerhard Wörner	Georg-August-Universität Göttingen
Prof. Dr. Peter Schlosser ML	Arizona State University, Tempe, Arizona (USA)

Working group

Prof. Dr. Onno Oncken ML	Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum (Speaker of the working group)
Prof. Dr. Jörg Bendix ML	Philipps-Universität Marburg
Prof. Dr. Friedhelm von Blanckenburg ML	Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum
Prof. Dr. Antje Boetius ML	Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven; Max-Planck-Institut für Marine Mikrobiologie Bremen und MARUM Universität Bremen
Prof. Dr. Martin Claußen ML	Max-Planck-Institut für Meteorologie, Hamburg
Prof. Dr. Christian Dullo ML	GEOMAR – Helmholtz-Zentrum für Ozeanforschung Kiel
Prof. Dr. Wilfried Endlicher ML	Humboldt-Universität zu Berlin
Prof. (ETHZ) Dr. Gerald Haug ML	Nationale Akademie der Wissenschaften Leopoldina
Prof. Dr. Heiner Igel ML	Ludwig-Maximilians-Universität München
Prof. Dr. Ulrike Lohmann ML	ETH Zürich
Prof. Dr. Joachim Reitner	Georg-August-Universität Göttingen
Prof. Dr. Hans Joachim Schellnhuber ML	Potsdam-Institut für Klimafolgenforschung
Prof. Dr. Peter Schlosser ML	Arizona State University, Tempe, Arizona (USA)
Prof. Dr. Gerhard Wörner	Georg-August-Universität Göttingen

Scientific Officers

Dr. Christian Anton	Nationale Akademie der Wissenschaften Leopoldina, Abteilung Wissenschaft – Politik – Gesellschaft
Dr. Henning Steinicke	Nationale Akademie der Wissenschaften Leopoldina, Abteilung Wissenschaft – Politik – Gesellschaft
Johannes Mengel	Nationale Akademie der Wissenschaften Leopoldina, Abteilung Wissenschaft – Politik – Gesellschaft
Dr. Sebastian Wetterich	Nationale Akademie der Wissenschaften Leopoldina, Abteilung Internationale Beziehungen

(ML = Member of the Leopoldina)

Peer review

Prof. Susan Brantley	Pennsylvania State University (USA)
Prof. Guy Brasseur	Max-Planck-Institut für Meteorologie, Hamburg
Prof. Sierd Cloetingh	Utrecht University, Department of Earth Sciences (Niederlande)
Prof. John Ludden	Heriot Watt University, Edinburgh (Schottland)
Prof. Susan Trumbore ML	Max-Planck-Institut für Biogeochemie, Jena

Workshops and hearings

On 12 November 2018 the working group invited experts to the workshop "Data Management & Data Infrastructure for Geosciences", where the following persons participated:

Prof. Dr. Bernd Bischl	Ludwig-Maximilians-Universität München
Prof. Dr. Stefan Dech	Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen
Dr. Anton Frank	Leibniz Rechenzentrum der Bayerischen Akademie der Wissenschaften, München
Prof. Dr. Frank Oliver Glöckner	Max-Planck-Institut für Marine Mikrobiologie, Bremen
Prof. Dr. Volker Mosbrugger ML	Senckenberg Gesellschaft für Naturforschung, Frankfurt
Prof. Dr. Monika Sester	Leibniz-Universität Hannover

A second workshop "Universitäre Ausbildung für die Erdsystemforschung" with the following experts took place on 3 December 2018:

Prof. Dr. Sabine Attinger	Helmholtz-Zentrum für Umweltforschung, Leipzig
Prof. Dr. Doris Breuer	Deutsches Zentrum für Luft- und Raumfahrt, Berlin Prof. Dr.
Torsten Dahm	Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum
Prof. Dr. Horst Malchow	Universität Osnabrück
Prof. Dr. Xiaoxiang Zhu	Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen

The following persons contributed with suggestions, reviews, and recommendations to this report

Prof. Dr. Fabrice Cotton	Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum (3.6)
M. Sc. Donovan Dennis	Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum (5)
Dr. Jonathan Donges	Potsdam-Institut für Klimafolgenforschung (3.4)
Prof. Dr. Dan Frost ML	Universität Bayreuth (3.1)
Prof. Dr. Dieter Gerten	Potsdam-Institut für Klimafolgenforschung und Humboldt-Universität zu Berlin (3.7)
Dr. Jürgen Grötsch	Shell Technology Centre Amsterdam (3.7)
Prof. Dr. Christian Hallmann	Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum (3.2)
Dr. Michael Henehan	Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum (3.4)
Prof. Dr. Jürgen Kurths	Potsdam-Institut für Klimafolgenforschung (2)
Dr. Joe Magnall	Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum (3.7)
Dr. Maria A. Martin	Potsdam-Institut für Klimafolgenforschung (3.6)
Prof. Dr. Ulrich Platt ML	Ruprecht-Karls-Universität Heidelberg (3.3)
Prof. Dr. Johan Rockström ML	Potsdam-Institut für Klimafolgenforschung (3.5)
Prof. Dr. Thomas Stocker ML	Universität Bern (3.3)
Prof. Dr. Manfred Strecker ML	Universität Potsdam
Prof. Dr. John Thompson	Cornell University, USA (3.7)
Prof. Dr. Martin Visbeck	GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel (3.3)
Prof. Dr. Friedrich Wellmer	formerly Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover (3.7)
Prof. Dr. Ricarda Winkelmann	Potsdam-Institut für Klimafolgenforschung (2 & 3.4)

The following persons gave additional valuable comments on a revised version of the report

Prof. Dr. Antje Boetius ML	Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven
Prof. Dr. Andreas Mulch	Senckenberg Biodiversität und Klima Forschungszentrum, Frankfurt
Prof. Dr. Ulrich Radtke ML	Universität Duisburg-Essen
Prof. Dr. Monika Sester	Senatskommission Erdsystemforschung der DFG und Leibniz Universität Hannover

(ML = Member of the Leopoldina)

This statement was funded solely by the German National Academy of Sciences Leopoldina, which in turn receives its core funding from the German Federal Government and the federal state of Saxony-Anhalt.

We thank all reviewers for helpful comments and all experts who contributed to the report.

Other publications of the series “Report on Tomorrows’s Science”

2021
Ageing and the Life Course – Research for Longer Lives

2014
Life sciences in transition – Challenges of omics technologies for Germany’s infrastructures in research and teaching

All publications are available for free in PDF format at:
https://www.leopoldina.org/en/publications

German Academy of Sciences Leopoldina
– National Academy of Sciences –

Jägerberg 1
06108 Halle (Saale)
Phone: 0049 345 472 39-867
Email: politikberatung@leopoldina.org

Berlin offices:
Reinhardtstraße 14
10117 Berlin

Unter den Linden 42
10117 Berlin

The Leopoldina originated in 1652 as a classical scholarly society and now has 1,600 members from almost all branches of science. In 2008, the Leopoldina was appointed as the German National Academy of Sciences and, in this capacity, was invested with two major objectives: representing the German scientific community internationally, and providing policymakers and the public with science-based advice.

The Leopoldina champions the freedom and appreciation of science. It promotes a scientifically enlightened society and the responsible application of scientific insight for the benefit of humankind and the natural world. In its interdisciplinary discourse, the Academy transcends thematic, political and cultural boundaries. It is also an advocate of human rights.

It is the role of the Leopoldina, in co-operation with other national and international organisations, to identify and analyse scientific issues of social importance. The Leopoldina presents its policy recommendations in a scientifically qualified, independent, transparent and prospective manner, ever mindful of the standards and consequences of science.

www.leopoldina.org