REKLIM

Helmholtz Climate Initiative
Regional Climate Change

THE CHALLENGE OF CLIMATE CHANGE | Questions of our time. Answers we need.

HELMHOLTZ
ASSOCIATION

Our climate – our future

Complex interactions with far-reaching impacts

Climate fluctuations are an essential feature of the Earth. They are documented by direct measurements, chronicles and biological-geological archives in tree rings, corals and ice and sediment cores. Variations in climate occur on time scales of weeks to millions of years. The current state of the climate is the result of the ongoing, continuous development of the past 4.5 billion years. During the course of geological history, there have been numerous pronounced climate fluctuations with clearly visible impacts, and they have always been a challenge for life on Earth, and certainly for humans. Impressive examples are the last ice-age cycles, in which large portions of the northern continents were at times covered by large ice sheets; the sea level in warm times was several metres higher and about 120 metres lower during the ice ages.

Climate fluctuations played an essential part in the developmental history of the Earth, and they will accompany us in the future as well. In the past, climate fluctuations occurred as the result of natural processes. They were the result of external forcing (e.g. changes to Earth's orbital parameters, volcanic eruptions and small changes in solar radiation intensity) and internal interactions in the climate system, which is composed of the atmosphere, the ice masses, the oceans, the land surfaces and all life forms on the continents and in the sea.

Recently, as a result of the huge increase in world population and rapid technological development, humankind has been put into a position of playing an active and effective role in shaping the climate. For instance, the global warming of the past 50 years has been largely caused by humankind, in particular as a result of the continuously increasing emissions of carbon dioxide from the intensive use of fossil fuels and changes to the land surface from agriculture, industry and settlements. As a result of this anthropogenic climate change, a significant global warming of approximately 3°C is expected in the next 100 years. Detailed studies of the physical causes of climate fluctuations and the response of the climate system to human intervention are currently the subject of national and international climate research (World Climate Research Programme, http://www.wcrp-climate.org/). A recent summary of the current knowledge about the climate system is represented by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (http://www.ipcc.ch).


REKLIM
Helmholtz-Verbund
Regionale Klimaänderungen

The climate change challenge

Collaborative climate research

Interactions between atmosphere, ice, ocean and land surfaces determine the climate of the Earth. In recent years, global climate models have been used successfully to establish an initial understanding of large-scale natural climate variability and human influence on the climate. However, many processes that affect the climate at various scales are not well understood. At this time, there exists a broad consensus in the scientific community that there is a high probability that the current warming of the Earth is mainly due to increased concentrations of greenhouse gases and changes in land use. The actual impacts for individual regions are still poorly understood, however. Whether climate change will determine, for example, that the summers will be drier or the winters wetter in a specific region has not been ascertained sufficiently through scientific investigation. For agricultural uses, however, this question is of crucial importance. For political and economic decision-making processes, detailed scenarios of the increase in sea levels, for example, are important to adapt coastal protection measures accordingly.

Eight research centres of the Helmholtz Association have come together to form the Helmholtz Climate Initiative Regional Climate Change (REKLIM), to find answers to the following questions: How does the development of the climate depend on the interaction between atmosphere-ocean-ice and land surfaces? What effect do natural and anthropogenic processes have? How large are the losses of the continental ice masses (in particular, Greenland) and how does the sea level react to melt water runoff and ocean warming? Which specific changes in soil, ocean and atmosphere in the shelf sea and permafrost regions of the Arctic are due to climate change and which interactions exist? What are the regional impacts of climate change on the ecosystem, water resources, agriculture and forestry and how do these in turn affect the climate? How is the regional climate affected by changes to the atmospheric composition? How will the severity and frequency of extreme weather events change in a future climate? Integrated climate policy comprises the mitigation of greenhouse gas emissions and adaptation to climate change. Is there an optimal route to be taken?

To answer these questions, scientists of the eight centres will improve on the data basis for their model calculations, as this is the only way to generate highly spatially resolved analyses and scenarios. Detailed observations and process studies will lead to optimised coupled climate models, which will illustrate the regional and local impact of changed conditions in the climate system. Thus, the researchers will be able in the future to better advise politics, the business community, agencies and the general public with scientifically based data and scenarios for decisions on regional development.

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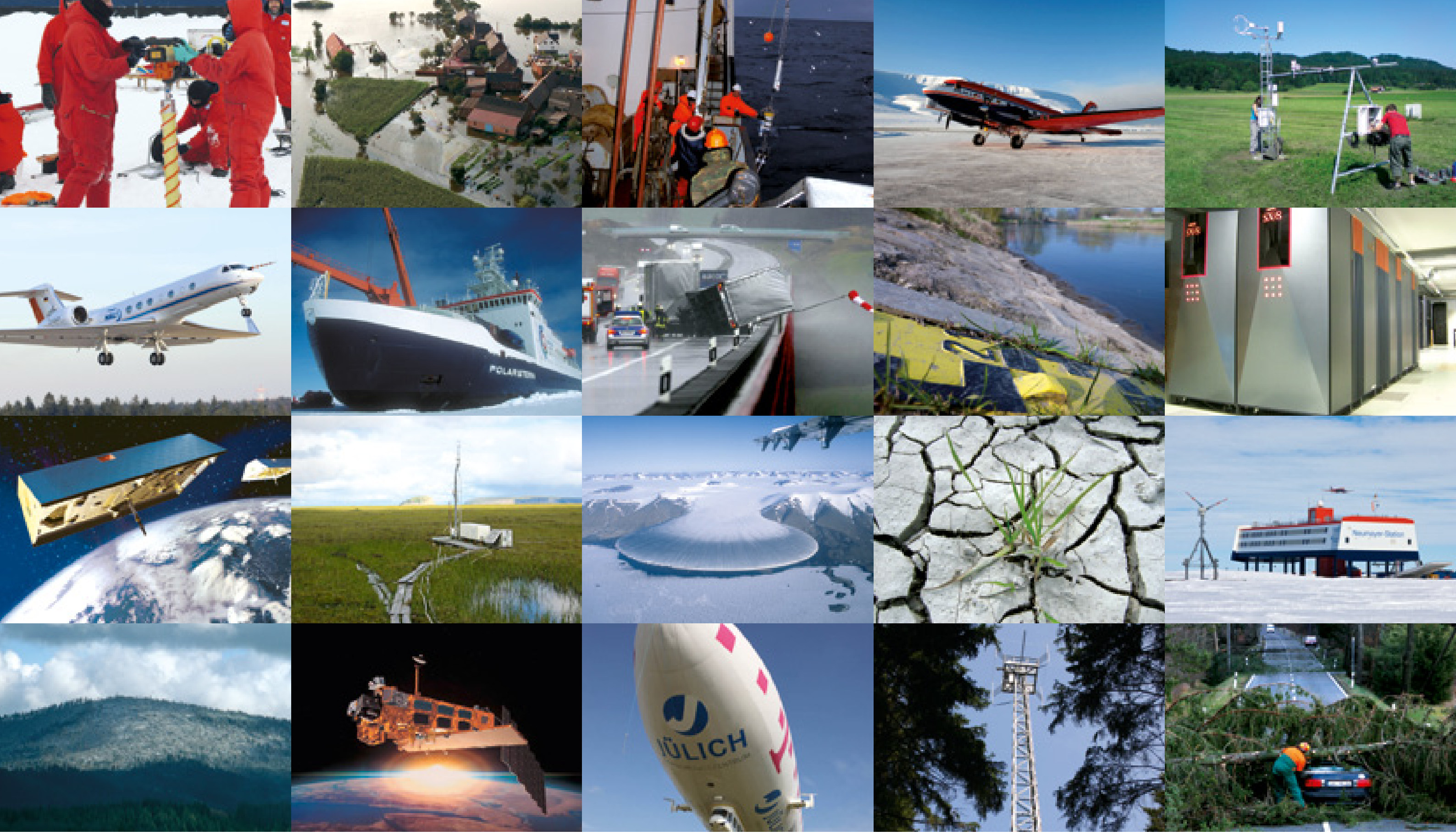

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Karlsruher Institut für Technologie
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Questions of our time.
Answers we need.

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Which specific changes of land, ocean, and atmosphere in the shelf sea and permafrost regions of the Arctic are due to climate change and which interactions exist?

What are the regional impacts of climate change on the ecosystem, water resources, agriculture and forestry and how do these in turn affect the climate?

How is the regional climate affected by changes to the atmospheric composition?

How will the severity and frequency of extreme weather events change in a future climate?

Integrated climate policies comprise the mitigation of greenhouse gas emissions and adaptation to climate change. Is there an optimal route to be taken?

1 Coupled modelling of regional earth systems

How does the development of the climate depend on the interaction between atmosphere-ocean-ice and land surfaces? What effect do natural and anthropogenic processes have?

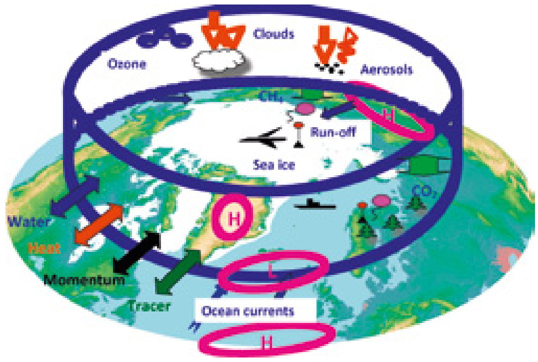

Fig. 1.1: The coupled climate system and its driving mechanisms for the Arctic model region. (Figure: Klaus Dethloff)

The Earth's climate is primarily characterised by large-scale structures of atmospheric circulation patterns and their temporal changes. Climate variations on seasonal and decadal time scales are influenced by climate variability resulting from external and anthropogenic factors as well as by the global dynamics of the coupled climate system with all its components. A close link between modelling and observation is necessary to analyse the dynamic and chemical processes in the atmosphere, to quantify the influence of the ice cover and oceanic processes on the atmosphere and to study the interactions between land surfaces, soil, vegetation and atmosphere. At the same time, the natural variability of the climate system must be taken into account. The climate system demonstrates variability on time scales ranging from seasons to decades as a result of nonlinear reaction to atmospheric fluctuations on time scales of days to weeks.

To be able to perform these types of studies, high-resolution, coupled climate models were developed for use at the regional scale, so-called Regional Earth System Models (*RESM* [1]), which are used as part of REKLIM in individual regions as a kind of magnifying glass, making it possible to generate regional climate data with higher spatial resolution (Fig. 1.2). This is particularly important and useful for regional decision makers. Special areas of investigation here are the Arctic, Europe and Germany.

The Regional Earth System Models consist of high-resolution atmospheric models and models for the ocean, sea ice, land surface, soil, *aerosol chemistry* [2], vegetation and other components (Fig. 1.1). The models are based on mathematical-physical basic equations using hydrostatic or non-hydrostatic approximations and parameterise process descriptions, which must be validated in detail through comparisons with data.

As part of *ensemble simulations* [3], during which a climate model is run multiple times with various initial or boundary conditions, an analysis is performed on the dependency of climate development on the interactions between the atmosphere, ocean, ice and land surfaces and the influence of natural and anthropogenic processes. One of the goals is to reduce existing uncertainties with respect to regional climate modelling and to be able to formulate robust conclusions.

The Alfred Wegener Institute (AWI) focuses on RESM in the Arctic; the Helmholtz-Zentrum Geesthacht (HZG) develops them for Northern Europe and Germany. The Karlsruhe Institute for Technology (KIT) and the Helmholtz Centre for Environmental Research (UFZ) focus their development on Central Europe and Germany. Land-surface and soil models are an important common ground between the participating institutions and are a focal point of the cooperation. In Figure 1.3 the diverse work packages of Topic 1 within REKLIM are shown. Their mutual interrelationships, the integration of different data sets and the connection to global model simulations is illustrated. The following scientific common ground will be worked on by the participating Helmholtz Centres jointly:

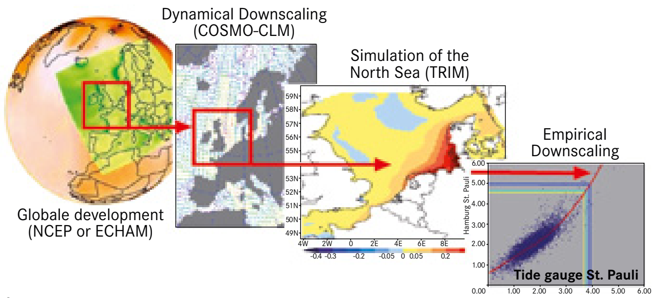

Fig. 1.2: Dynamic downscaling cascade („magnifying glass") with regional climate models for Europe and the Baltic Sea. The acronyms of the models used are given in parenthesis. (Figure: Hans von Storch)

Atmosphere, ocean, sea-ice and permafrost feedbacks

The simulation of arctic sea-ice cover with coupled atmosphere–ocean–sea-ice models is associated with a high level of uncertainty. Using the combination of improved *parameterisations*[4] for ice growth, the snow and *ice albedo*[5] and the snow cover on ice, a more realistic representation of these feedback processes will be achieved in the coupled regional climate model *HIRHAM-NAOSIM*[6]. The simulation of land-surface and soil processes in arctic *permafrost regions*[7] is an important aspect in the regional climate modelling of the Arctic, for which the development of a modular Regional Earth System Model of the Arctic with components for permafrost will be continued. Previous results indicate that the performance of an RESM depends on a realistic representation of feedback processes between the individual model components (atmosphere: HIRHAM, ocean and sea ice: NAOSIM and permafrost: *LSM*[8]). For the North Sea and Baltic Sea, the regional atmospheric model *COSMO-CLM*[9] will be also coupled with a regional ocean model and a sea-ice model. The goal is an improved temporal and spatial simulation of regional characteristics such as storm surges and ice cover.

Aerosol , cloud and trace-gas effects on the climate of Europe

The model system *COSMO-ART*[10] has been further developed to handle processes that are associated with secondary aerosols, directly emitting components – such as soot, mineral dust and sea salt –, clouds and chemical constituents as well as with biological material such as pollen. The model system has been used to simulate the effect of aerosol particles on radiation and clouds during meteorologically relevant episodes and in conjunction with volcanic eruptions. As a part of REKLIM, it will be used on the decadal time scale. The effect of trace gases and aerosol particles on the climate in Europe can therefore be quantified with an unprecedented level of detail.

Effect of land-surface and soil processes on the regional climate

Through memory effects, land-surface and soil processes play an important role in regional climate simulations on decadal time scale. To investigate the effect of vegetation coverage, soil parameters and the freezing and thawing of water in the soil, the global Community Land Model (CLM) wil be adapted to the regional scale to be able to use it with regional climate models. Using convection-resolving simulations with the RESM COSMO-CLM, the effect of land-use change will be evaluated for the climate in northern Germany. A more realistic representation of cities and more differentiated land use in the RESM will illustrate this anthropogenic effect on the climate. In addition, an estimate will be made as to how the climate changes due to CO_2 scenarios can also be modified by land-use changes.

Influence of internal variability and emission scenarios on the regional climate

The uncertainties of climate scenarios of the coming decades will be reduced by ensemble simulations and the effect of internal variability of the climate system, as a result of atmospheric teleconnection patterns, and of emission scenarios on extreme events will be quantified. The interannual variability of precipitation was studied with the COSMO-CLM for Central Europe. In this case, the change of the standard deviation of the precipitation with respect to the total precipitation was compared on the basis of an ensemble of 30 regional climate model simulations for two periods, 1971-2000 and 2011-2040. The ensemble shows an increase of the interannual variability in the 2011-2040 period, which is most pronounced in summer (8%) and autumn (14%). An increased variability of the precipitation suggests that the likelihood of years with extreme droughts, as well as extremely heavy precipitation, could increase.

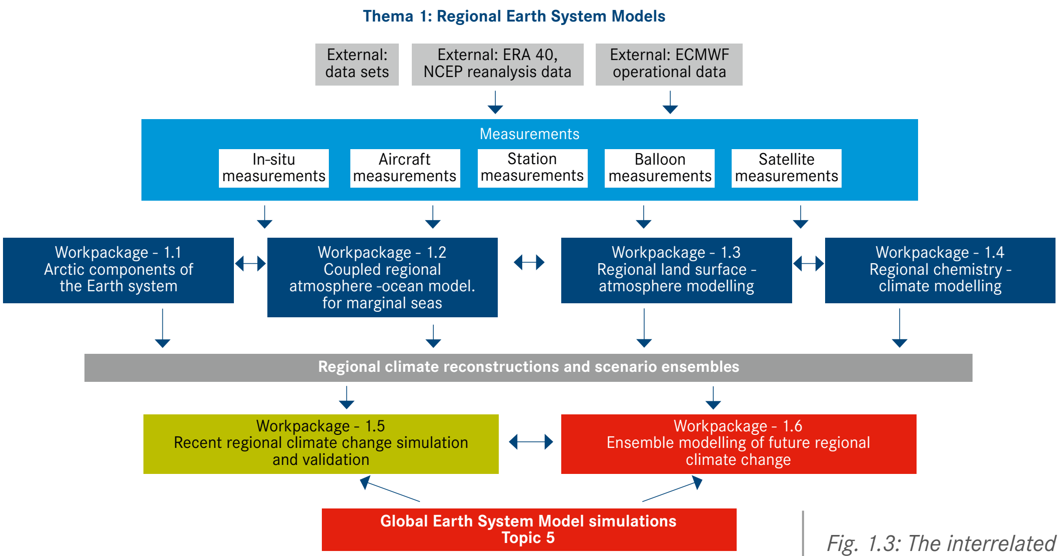

Fig. 1.3: The interrelated work packages of Topic 1. (Figure: Klaus Dethloff)

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2 Sea-level changes and coastal protection

How large are the losses of the continental ice masses (in particular, Greenland) and how does the sea level react to melt water and ocean warming?

In the past 3000 years, in which human civilisation has been predominately settled along coasts, the sea level has changed only slightly. Port and city planners only needed to account for storm surges, but not for a rise in the sea level. This has changed in recent decades, as the sea level is rising currently at 3 mm/year. The cause is the increased melting of mountain glaciers and melting of large ice sheets on Greenland and in the Antarctic due to the higher atmospheric temperatures resulting from climate change.

Ice mass balance

Currently, the melt rate of the ice masses worldwide is increasing and contributes about 40% to the global sea level rise. The largest contribution is currently made by the melting mountain glaciers. In the longer term, however, the behaviour of the Greenland ice sheet will be crucial. Currently, it is losing more mass at the edges due to glacier discharge and melt water runoff than snow is accumulating at the central higher altitudes. The result is a net loss of mass, which contributes to sea level rise.

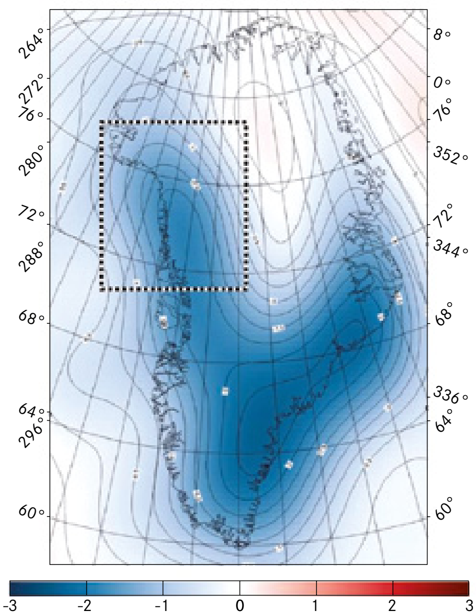

Fig. 2.1: Observed changes of the Earth's gravitational field above Greenland captured with the GRACE satellite mission, from which the loss of ice mass in Greenland can be calculated. In north-west Greenland alone (marked area), the ice cover reduces by about 46 billion tons per year, corresponding to a sea-level rise of 0.13 mm/year. (Figure: Ingo Sasgen)

The changes in the Greenland ice sheets can be derived from the gravity data (measuring the force of Earth's gravity) of the *GRACE satellite mission*[11]. The previous results of the satellite mission, which has been in operation since 2002, indicate in particular for the southeast and northwest of Greenland a significant decrease of the ice, which has accelerated significantly in the northwest in the past few years (Fig. 2.1).

Similarly, using satellite observations regions in the Antarctic can be identified that show a particularly sensitive reaction to climate change. While on the Antarctic Peninsula warming above the global average is currently being observed, as well as the collapse of large ice shelf areas, in the Amundsen region of the West Antarctic the greatest flow rates are occurring and thus mass loss of the southern polar ice cap.

Unresolved questions here relate in particular to knowledge of the glacier and ice flow dynamics and the response of the ocean to warming and the supply of melt water, in particular near the coast. With the help of high-resolution models of ice sheet dynamics, which are capable of reproducing the physical properties in flow dynamics of the outlet glaciers, REKLIM will investigate how the mass outflow through the large outlet glaciers will respond to the changed climate conditions. Here the conditions at the bedrock are of crucial importance: Do the glaciers flow slowly because they are frozen to the ground or do they lose their adhesion and accelerate due to the melting processes at their base? This is particularly important for the mass flow of ice out of the inland into the coastal region, where the ice melts much more quickly. These investigations are supported by in-situ observations and airborne, high-resolution radar measurements, which make it possible to determine the internal structure and properties of the ice-bedrock interface (Fig. 2.2).

Fig. 2.2: The research aircraft Polar 5 of the AWI on the runway of Longyearbyen, Spitsbergen, at the start of a measurement flight. (Photo: Johannes Käßbohrer)

Global changes in sea level

If the ice has melted and flows to the ocean as freshwater, it affects not only the sea level, but also changes the ocean current, as the freshwater is lighter due to its lower density and lays on the sea water like a lens. This causes the vertical mixing of the water column (convention) to be suppressed, with effects on deep-water formation and thus the global *thermohaline circulation*[12]. Using a Global Earth System Model, this effect, in combination with the long-range effects of the change to the gravitational field on the ocean current, is studied.

For a melt rate estimated at 200 billion tons per year from Greenland, the rise in the sea level was calculated. In a regionally high-resolution ocean model, the melt rate and the melt region were specified according to the satellite measurements. The simulation for the first 16 years is shown in Figure 2.3. Globally, the result is a rising sea level of 0.6 millimetres per year. Changes in density are limited to the North Atlantic. They spread out slowly and affect primarily the coasts of Canada and Europe.

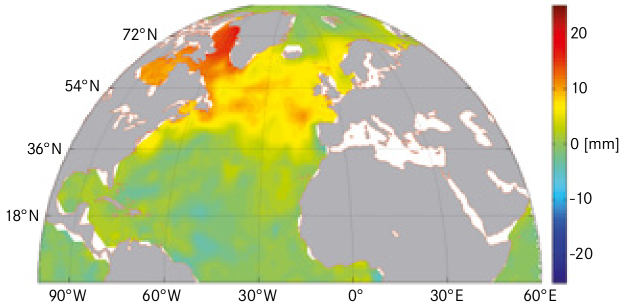

Fig. 2.3: Simulation of the sea-level change after 16 years with a global ocean model as response to a melt water runoff of the Greenland ice cap of 200 billion tons per year. The colour scale describes the increase in millimetres. The increase is spreading only slowly in the North Atlantic and affects mostly the coasts of Greenland as well as Canada and Europe. (Figure: AWI)

Regional effects

Regionally, however, significant deviations from the global mean sea level rise may occur. How the regional sea level at the coasts of the German Bight changed in the past century, whether an acceleration can be discerned in recent years and whether individual tide-gauges are representative for the evaluation of changes in the regional sea level: these issues have been evaluated using homogenised tide-gauge records at 15 different locations for the German Bight using two different methods (Fig. 2.4). Both methods result in similar time series, which differ, however, with respect to the decadal trends. Based on the analysis, it is assumed that the regional sea level in the area of the German Bight in the period from 1924 to 2008 rose by about 1.64 mm/year to 1.74 mm/year. The rates of increase are generally higher at the Schleswig-Holstein coast as at the coast of Lower Saxony.

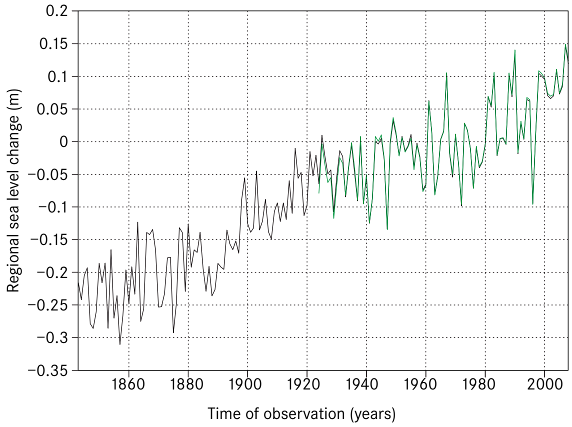

Fig. 2.4: Regional average sea level for the German Bight determined with two different methods (mean approach 1843-2008 (black); EOF method 1924-2008 (green)) derived from 15 tide-gauges in the German Bight. The period 1843-1924 is only given for one tide-gauge, three additional time series exist for the period since 1900. (Graphic: HZG)

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3

Regional climate changes in the Arctic: Forcing and long-term effects at the land-ocean interface

Which specific changes of land, ocean, and atmosphere in the shelf sea and permafrost regions of the Arctic are due to climate change and which interactions exist?

The polar regions play an especially important role within the Earth's climate system: the high *albedo*[5] of the sea ice and the ice- and snow-covered land surfaces largely determine the radiation balance of the Earth; the continental ice sheets constitute the largest reservoir of fresh water thus also the largest potential for sea level changes; the massive and deep-reaching *permafrost*[7] contains large amounts of organic carbon. The processes in the atmosphere, ocean, and land of the Arctic are closely interconnected. Therefore, understanding the internal mechanisms such as the *ice-albedo-feedback*[13], the energy and water fluxes, as well as the greenhouse gas emissions of the thawing terrestrial and submarine permafrost is of utmost importance for the development of climate models. Super-imposed on these mechanisms is the growing influx of oceanic and atmospheric heat from lower latitudes into the polar regions. At several sites around the Arctic Ocean these mechanisms are investigated through process studies as well as long-term monitoring (Fig. 3.1).

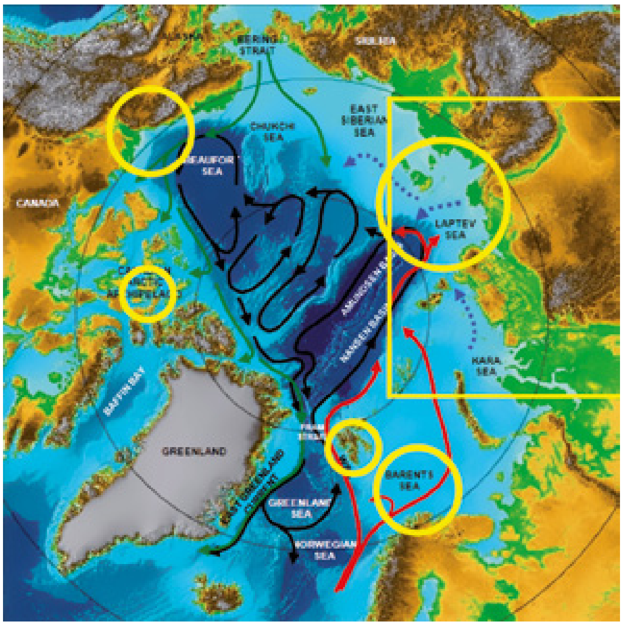

Fig. 3.1: Map of the marine and terrestrial study areas (marked in yellow). The arrows show ocean currents. (Figure: Ursula Schauer, Bert Rudels).

The natural emission of greenhouse gases (e.g. methane) is a result of both biological and geological processes. Both are studied and quantified through in-situ measurements, biogeochemical analyses, and numerical simulation. Emissions from biological processes are measured using closed chambers as well as micrometeorological methods in the Lena River Delta, Siberia (Fig. 3.3).

Additionally, emissions from methane reservoirs are investigated in the Mackenzie Delta, Canada. Here, numerical simulations of abiotic methane genesis in the deep sediment basin throughout geological time spans are combined with data on gas migration and its sequestration in the form of gas hydrates. Evidence of previous emissions are clearly visible in so-called "pockmarks" on the sea floor, e.g. in the Barents Sea off Norway. Within REKLIM, samples were taken from the sea floor to analyse the nature of these emissions, their chronology, and the sources. The combination of process understanding, measurements, and numerical simulations across human and geological time spans will enable us to better understand the previously insufficiently studied rates and dynamics of natural greenhouse gas emissions.

Trends in permafrost landscapes can only be discovered through long-term monitoring. To understand the underlying processes, we measure energy, water, and greenhouse gas fluxes at the Russian-German Research Station Samoylov in the central Lena River Delta, Siberia. The research station was established by the Lena Delta Reserve and the Alfred Wegener Institute for long-term research. A circum-Arctic service for operational remote sensing is currently implemented in collaboration with the International Permafrost Association (IPA) and the European Space Agency (ESA). Through remote sensing, large-scale surface temperatures, soil moisture, freeze-thaw processes, surface deformation, the extent of flowing and standing water, and methane concentrations are recorded and adapted as input parameters for permafrost and climate models. Once adapted to the study area, the regional climate model *COSMO-CLM*[9] will reconstruct climate-relevant parameters of the past 50 years for the region between the Laptev Sea and Yakutsk. This data set will have a high temporal and spatial resolution and will be the basis for statistical analyses.

Fig. 3.3: Micrometeorological system for temporally and spatially highly resolved measurements of greenhouse gas fluxes between tundra and atmosphere in the Lena River Delta, Siberia. (Photo: Torsten Sachs)

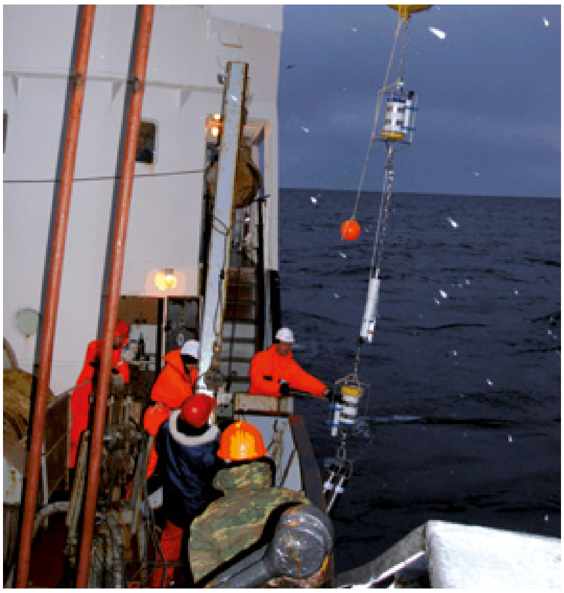

Fig. 3.2: Deployment of a mooring in the Laptev Sea. For an entire year, the instruments register changes in currents, water temperature, and salinity due to sea ice formation and river water influx from the Lena River. (Photo: Heidi Kassens)

The sea ice retreat will first affect the Arctic shelf seas. Therefore, we study the effects on circulation and on the modification of water masses in the Laptev Sea as an example (Fig. 3.2). During few weeks in summer, this shelf sea receives large amounts of river water from the Lena River including particulate and dissolved material. The fresh water has a stabilizing effect in the central Arctic and isolates warm ocean water from the sea ice. Additionally, the Laptev Sea is characterized by a large polynya (an extended ice-free area) during winter, where a large part of the Arctic sea ice and deep water is generated. Through a combination of single autonomously year-round measuring moorings, large-scale surveys of hydrography during summer expeditions and remote sensing, and numerical modelling, these processes are studied under changing sea ice conditions.

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4 The land surface in the climate system

What are the regional impacts of climate change on the ecosystem, water resources, agriculture and forestry and how do these in turn affect the climate?

We still know too little about the environmental changes triggered by global change and the associated consequences. Climate exerts a great influence on the land surface, just as land surfaces affect the climate. At present, however, we lack environmental data that have been collected in smaller regions and over a longer period. Only with this kind of data is it possible to detect and explain long-term regional changes and to develop necessary mitigation and adaptation strategies. The large, long-term monitoring programme *TERENO*[14] closes this gap (Fig. 4.1). As a part of TERENO, four observatories are currently being established in Germany: The Eifel–Lower Rhine Basin in the west, the northeast German lowlands characterised by ice-age influences, the Leipzig-Halle region in central Germany, and the Alps and Alpine foothills in the south together form a representative cross section of the German landscape types.

Location of the TERENO observatories in Germany

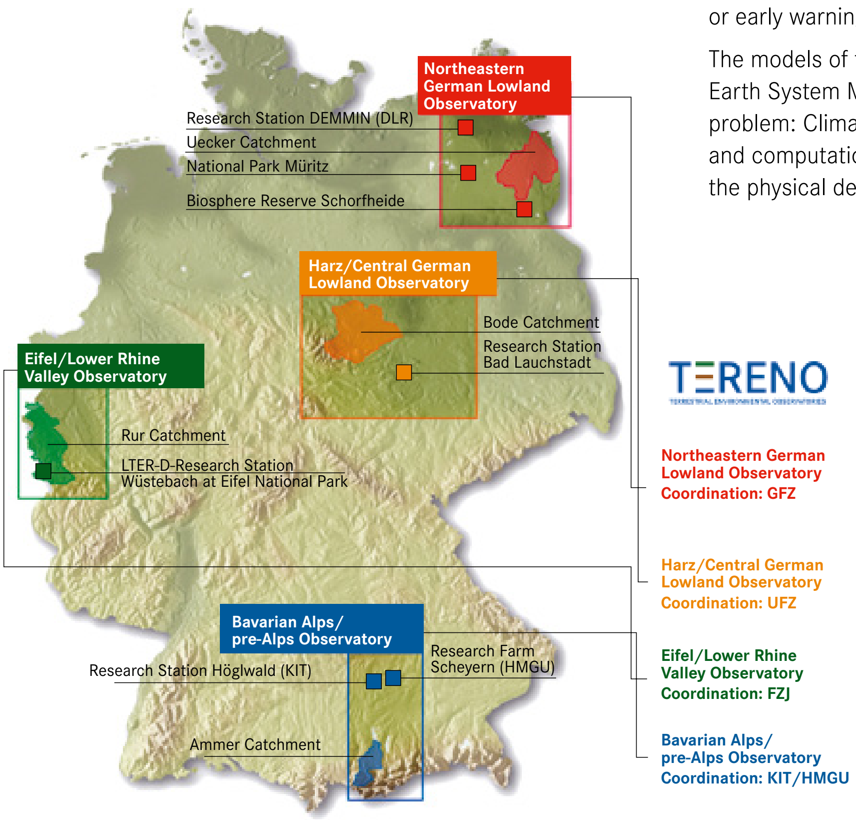

Fig. 4.1: The four TERENO observatories, as representations of typical German landscapes, are currently under construction. (Figure: TERENO Newsletter, December 2008; www.tereno.net)

Using modern techniques from environmental engineering, geophysics and remote sensing, environmental data from ground, aeroplane and space-based sensors are recorded, in particular observations on water and soil quality, vegetation and biological diversity. TERENO draws on the existing measurement stations of the Helmholtz Association, expands on them or establishes new ones (Fig. 4.2). Mobile measurement platforms are used, as well.

TERENO provides unique data on the interactions of vegetation and climate, which can also be used to test computer models of the land surface. These models consist of mathematical formulas that reflect our current understanding of plants, soil, the landscape and their interactions. By comparing the calculations of the models with the observed data from TERENO, our understanding of nature is evaluated. Within REKLIM existing models of the land surface are tested thoroughly and then further developed. Using the model results, measures for adaptation to climate change can be developed, such as optimised agricultural irrigation systems or early warning systems for heavy rain or storms.

The models of the land surface are also integrated in coupled Earth System Models of Topic 1. And there is the crux of the problem: Climate models are some of the most complicated and computationally intensive computer models that simulate the physical details of the Earth. As many as possible relevant

Fig. 4.2: C. Jahn and K. Heidfeld at the final installation of the Fendt eddy-covariance measurement station in the TERENO pre-alpine observatory. (Photo: Matthias Mauder)

components and interactions are taken into account – in the atmosphere, the oceans and on the Earth´s surface – and coupled with one another depending on the issue at hand. Even with the use of high-performance computers and simplified representation of climate-relevant processes, the necessary computing power is so great that the spatial resolution of global climate models is only between 50 and 250 kilometres. This is not sufficient to estimate climate impacts for countries or regions and to develop appropriate adaptation strategies. Small-scale processes or extreme weather events fall through the gaps in this coarse grid. For instance, if one wants to estimate the temporal and spatial distribution of future water resources, hydrological as well as regional climate models must be used, improved and coupled with one another (Fig. 4.3). However, only recently have regional climate models even been capable of working in small grid sizes of around 10 kilometres. For a long time they were unable to go below a grid size of 50 kilometres, which is too large for hydrological forecasting. Conversely, only in recent years were numerically efficient schemes developed for hydrological models, with which vertical processes such as soil moisture dynamics can be regionalised on larger scales. Thus, it is now possible in principle to couple climate and hydrological models with one another and to provide hydrological scenarios along with the climate scenarios. REKLIM will make an important contribution in this area.

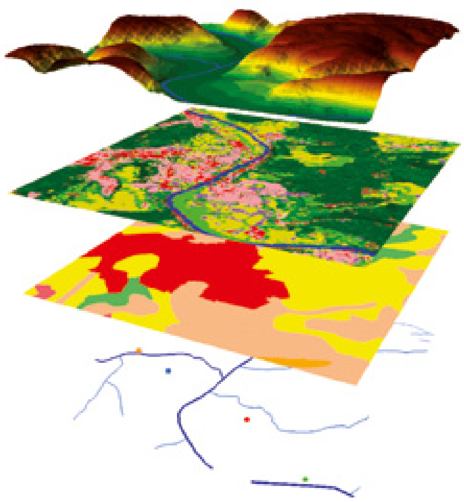

Fig. 4.3: Many physical, chemical and biological processes overlap at the interface between atmosphere and land surface. Better understanding of the relationships between these processes is the key for improved forecasting of regional climate change and its consequences for humans. (Figure: Dr.-Ing. Karl Ludwig, Wasserwirtschaft-Wasserbau GmbH, Karlsruhe)

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5 Chemistry-climate interactions on global to regional scales

How is the regional climate affected by changes to the atmospheric composition?

It is indisputable that carbon dioxide (CO_2) has been the greatest contributor to global climate change. However, there are also a number of trace gases and suspended particles (*aerosols*[2]) in the atmosphere that are important for the climate and climate-relevant processes. These components of the air (many of them particularly important at the regional scale due to their short lifetime) can lead to changes in the solar radiation budget and thus affect the regional climate. As part of REKLIM, using measurements of these atmospheric trace gases and numerical modelling, the effects of ozone, aerosols, water vapour and clouds on the climate system are studied. Together, this work will lead to better understanding of the most important climate-related processes in selected regions.

Atmospheric concentrations of air pollutants and climate-relevant air particles are determined by complex interactions of emissions, chemical transformations, transport and storage or removal via precipitation. To investigate these processes, scientists of the participating research centres use a variety of measurement instruments on various platforms (ground-based, zeppelins, research or passenger aircraft, satellites, ...) or in controlled environments (atmospheric simulation chamber) (Fig. 5.1). These data are compiled and analysed jointly in REKLIM. Complex numerical models of chemical and transportation processes in the atmosphere are essential for the interpretation of the observed data and are also used to examine the short-term or longer-term changes in the chemical composition of the atmosphere and the impact of these changes on the climate.

Focal points in REKLIM include studies of ozone and aerosols in the troposphere as well as ozone and water vapour in the stratosphere (Fig. 5.2). Ozone is formed in the atmosphere by photochemical processes, and in addition to being an air pollutant, it is also a greenhouse gas. The future development of ozone concentrations in the atmosphere is, however, a complex phenomenon: It depends on changes in the emissions of ozone precursors (nitrogen oxides and so-called volatile organic compounds), changes in temperature, precipitation, the frequency of lightning and incident ultraviolet radiation. Conversely, increased ozone concentrations near the ground can also affect the emissions of hydrocarbons from plants and thus indirectly affect the climate.

Aerosols are currently the only air components that could possibly counteract global warming, as they tend to increase the scattering of the incident sunlight back into space. However, there are as yet no reliable results concerning how the diverse composition of aerosols ultimately impacts the climate system. For example, the cooling effect of light sulphur aerosols may be compensated by the additional warming resulting from the strongly absorbing dark soot aerosols. Of particular interest for REKLIM are those aerosols that are formed from hydrocarbons that plants release under stress as well as aerosols resulting from the combustion of biomass.
An additional focus of the research in Topic 5 relates to water vapour and clouds in the upper troposphere region and the entry of water vapour into the stratosphere. Changes in the atmospheric trace gases at these high altitudes have a particularly high impact on the climate. It is therefore extremely important to precisely understand the dynamic chemical interaction

Fig. 5.1: Illustration of diverse measurement platforms that can be used in the association for determination of chemical composition of the atmosphere. From top to bottom: the satellite GRACE[11] *(source: GFZ), with which the water content of the atmosphere can be measured, an Airbus passenger aircraft, on which trace gas measurements are performed as part of the MOZAIC and IAGOS projects (source: Lufthansa), the NT zeppelin, which is used for trace gas and aerosol measurements in the lower atmosphere (source: FZJ) and the SAPHIR atmosphere simulation chamber, with which atmospheric chemical processes are investigated under controlled conditions.*

processes at this altitude and to obtain reliable data of water vapour distributions and changes in concentration using various measurement platforms.

The research activities in REKLIM are closely linked with large international programmes and are coordinated via the broad network of Helmholtz scientists with colleagues in Europe and further abroad. The development of new measurement instruments and new types of observation platforms contributes to the further development of the global system of earth observation, as does the participation of the researchers in the development of an operational European forecasting and analysis system for air components.

In the start phase of REKLIM, initial success has already been achieved through improved collaboration of the Helmholtz Centres. For example, the shared use of *radio occultation data*[15] of two satellite instruments with the in-situ measurement data from a research programme on passenger aircraft was able to provide a description of the troposphere regions relevant for the climate system at an unprecedented level of detail. For the first time, data records of different observation platforms were combined to form a global climatology of water vapour in the stratosphere (Fig. 5.3). The centres also work closely together on the creation of global emission inventories for the next world climate assessment report and drive the development of coupled chemistry-climate models.

A key objective of Topic 5 is the development of improved physical and chemical parameterisations in global and regional chemistry-climate models. From detailed process studies, general relationships are derived, which can then be integrated into the model systems in mathematical terms. These *parameterisations*[4] are then evaluated by carefully comparing multiple short-term simulations (roughly one year in length) with the available observed data. Finally, longer simulations with coupled chemistry-climate models will make possible better understanding of the dynamic chemical interactions and enable improved quantification of the effect of short-lived trace gases and aerosols on regional climates.

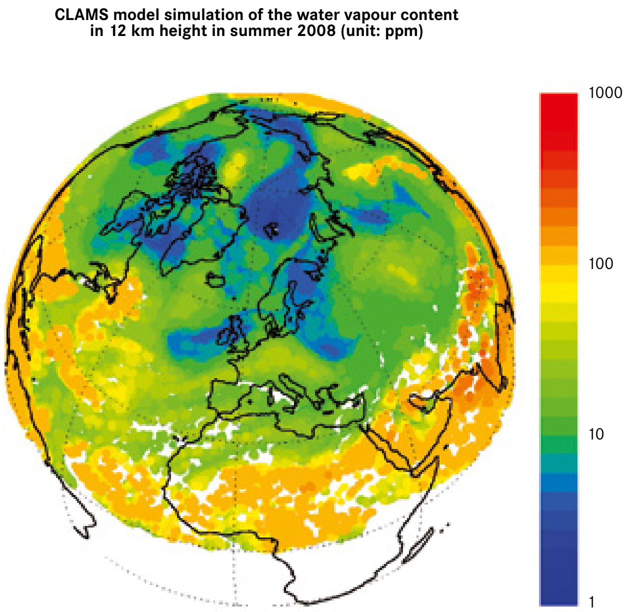

Fig. 5.3: Model simulation of the water vapour distribution at 12 km altitude in the summer of 2008. Elevated water vapour vapour levels in the tropics are clearly visible (yellowish colours). (Figure: FZJ)

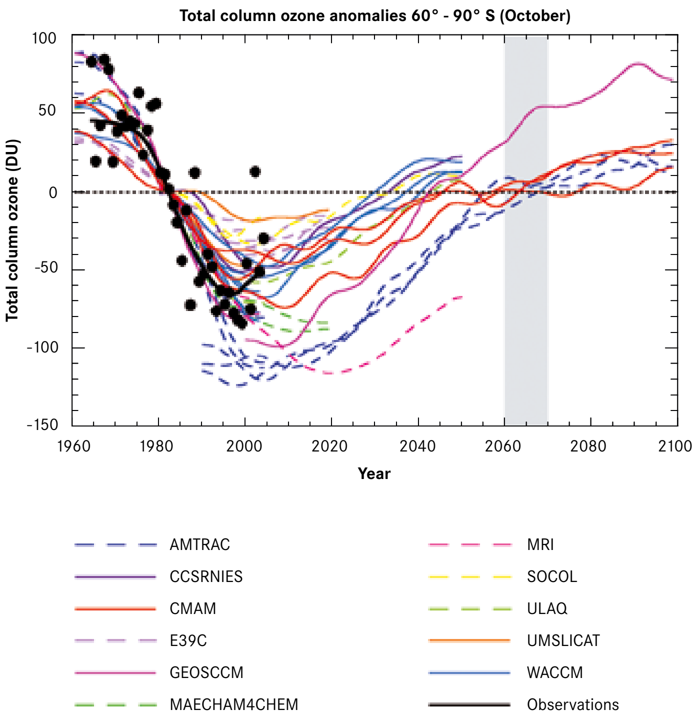

Fig. 5.2: The ozone hole is expected to disappear by the end of this century; however, model predictions show significant differences over time. Model results from an international model comparison are shown in colour, the observed data are shown in black for comparison. The recovery of the ozone layer has significant effects on the global climate system. (Figure: SPARC report on the evaluation of chemistry-climate models, WMO-TD No. \ 1526, WMO, Geneva, 2010)

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KIT | HZG | GFZ | UFZ

6 Extreme weather events – storms, heavy precipitation, floods and droughts

How will the severity and frequency of extreme weather events change in a future climate?

The study of extreme weather events (Fig. 6.1) and their regional characteristics and changes resulting from climate change in the past and the future is a great challenge of our time. The consequences of extreme weather events are determined by the current weather conditions during climate change and by the vulnerability of living spaces, habitats and technical infrastructure, which are subject to constant change. Here the challenge is to use all available data sets and detailed modelling to better understand the variability of rare extreme events and to quantify them by using appropriate statistical methods. The topic is thus highly relevant for application purposes and the results serve as a basis for adaptation measures.

The participating Helmholtz Centres have come together within REKLIM to explore and assess the essential types of hazards and consequences of extreme weather events in present and future climates. In this context, the following topics are assessed in more detail.

Evaluation of previous extreme events using *proxy data*[16]

For several types of extreme events, the use of proxy data (such as documented flood events) has been suggested to explore the connection with physical state variables, which has not yet been resolved satisfactorily. Such relationships will therefore be investigated using Regional Earth System Modelling. Here, model-based relationships between seasonal states of the climate system at the continental scale and the associated extremes are used.

Extreme events and runoff modelling

The hydrological processes at the Earth's surface are influenced by climate change, through which increased risk is expected of extreme events such as droughts and floods associated with large annual losses. For such events, for the period before instrument observations (the last 200 years), proxy data is available that is to be validated with a hydrological model (mHM). Here a comprehensive comparison of modelled water levels in deep soil layers and surface runoff is performed with measured data of runoff and high water levels as well as drought proxies, such as tree rings.

Validation of Regional Earth System Models with respect to extreme value statistics of storms, precipitation and hydrological events

The statistical uncertainty of return values of rare, extreme weather events from observation and model data is quite high and depends on the type of the fitted distribution function, the spatial and temporal density and the representativeness of the data. For this reason, different extreme value statistics methods are applied to determine from an *ensemble*[3] of Regional Climate Models the most appropriate models and model combinations to reduce the uncertainty of the results and to quantify them. Here, extensive measurement data of operational services, such as the German Weather Service, are used as well as previously rarely used information, e.g. those from oil platforms, offshore wind farms, and insurance data.

Statistical features of extreme events in recent decades

Statistics of extreme weather events, in particular the changes for the individual seasons, are derived from the results of Regional Earth System Models for periods of years to decades. Their connection with circulation indices, with the help of which large-scale fluctuation patterns in the climate system are described, is exploited for various regions and events, such as North Atlantic storms, polar lows, typhoons in Southeast Asia and storms in the Mediterranean. The connection to extreme oceanic events (sea state, extreme waves) will be examined.

Extreme events in scenarios of future climate change

The ensemble of high-resolution regional climate simulations from Topic 1 serves as the basis for statistical analysis of winter storms, heavy precipitation events, hail, inland and coastal floods as well as droughts. Due to the features of the adapted distribution functions, which reflect trends and return periods, changes in the extreme values for future periods with respect to the validation period are determined, as well as their statistical confidence level.

Flood risk and management

For dealing with the presumed growing threat from floods, in the political and administrative arenas, a change needs to be made from the classic concept of „flood control" to „flood management" (see the EU Flood Directive 2007/60/EC). Building on the

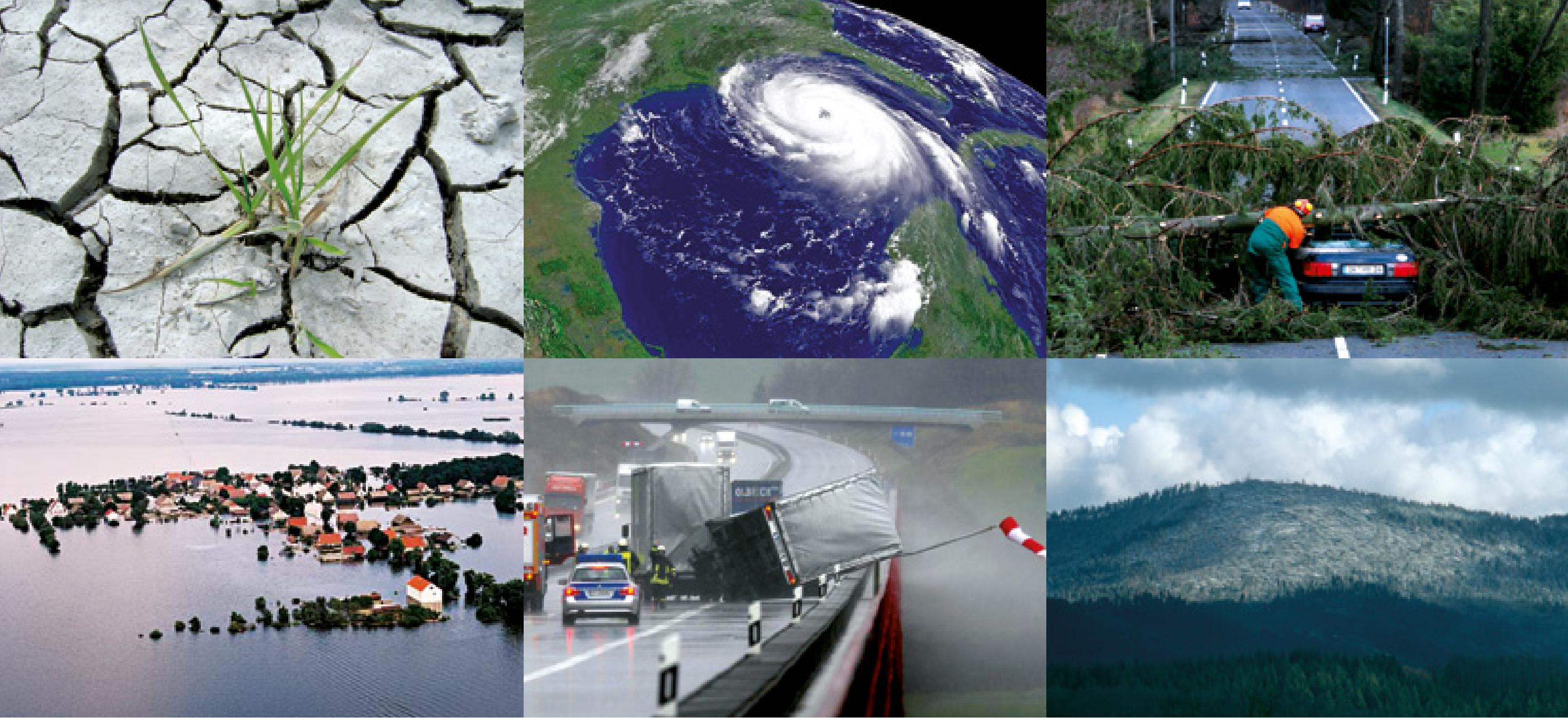

Fig. 6.1: Illustration of the most relevant extreme weather systems and their effects: Heat waves with droughts, tropical cyclones, winter storms, floods, high winds and tornadoes. (From left to right. Photo 1: © VGMeril/PIXELIO, photo 2: © Reuters, photo 3: © picture-alliance/dpa, photo 4: © German Federal Government/Kühler, photo 5: © dpa, photo 6: © Georg Müller)

scientific simulation results, the concepts for participatory and integrated risk assessment, risk management and decision support are developed. The quantification of flood impacts is expanded to include effects on the environment, the biosphere and biodiversity as well as contamination via transported pollutants.

Previous results

Through the work at HZG, it has become clear that decadal fluctuations in particular determine the storm variability in the regions analysed in the Pacific and North Atlantic. Uniform trends were not found. HZG and KIT are also investigating the expected changes of storm frequency in Germany and Europe on the basis of regional climate model simulations with varying resolutions. For the coming decades, a slight increase in storm frequency in Northern Germany is becoming apparent. At KIT, a detailed hazard map for winter storms over Germany has been calculated for the past, which is also increasingly used by insurance companies. KIT deals with future trends of inland precipitation using regional climate simulations with a focus on small and medium-sized catchment areas. Complementary to this work, runoff modelling is being performed by GFZ and KIT. GFZ analysed the flood trends of the last 50 years in all large catchment areas in Germany and is developing a method for nationwide flood risk assessment, taking potential changes to vulnerability via land use into account. At UFZ, fundamental studies are being performed regarding suitable distribution functions of precipitation and runoff as well as for generation of synthetic precipitation time series for runoff calculations. A new topic is the estimation of trends of severe hailstorms and related convection indices at KIT, for which an increase could be detected using insurance data and meteorological measurements over recent decades (Fig. 6.2). In southern Germany, hail causes the highest level of yearly insured losses regarding buildings.

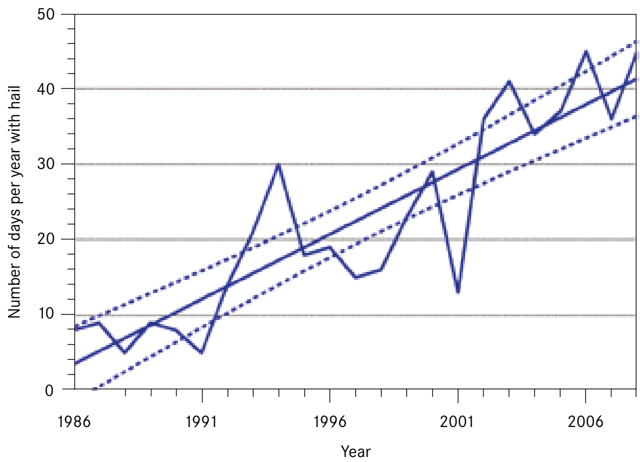

Fig. 6.2: Change in the number of hail days, derived from insurance data, with linear trend and confidence interval (95% significance) in previous decades over Baden-Württemberg. The change is almost consistent with that of several convection indices. (Figure: Michael Kunz, KIT)

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7 Socio-economics and management for regional climate change adaptation and mitigation strategies

Integrated climate policies comprise the mitigation of greenhouse gas emissions and adaptation to climate change. Is there an optimal route to be taken?

Limiting global warming in the long run to two degrees Celsius will require a tremendous effort worldwide. Global carbon emissions would have to be continuously reduced, instead of increased as in the past. In fact, only if they are reduced to half the level of the base year 1990 by 2050, could the political goal of the climate summit in Copenhagen be accomplished. Furthermore, even if a change in the trend of worldwide carbon dioxide emissions succeeded, on the long road to a stable climate we would have to live with regional temperature increases of 4 degrees Celsius and more. Needless to say, adaptation to climate change is a global necessity!

Adaptation to climate change means that we will reduce our vulnerability to the impacts from global warming. While in Germany, we must prepare ourselves better for heat waves in summer and heavy precipitation events in winter, other countries will be primarily concerned with counteracting the impacts from sea level rise, extreme water shortages, and the loss of sensitive ecosystems such as coral reefs. The countries in the South will suffer the most from global warming, while the countries in the North might even benefit from it temporarily. With increasing global warming however, these advantages will be short-lived, so that in the long-run we will have to count on net negative impacts of climate change.

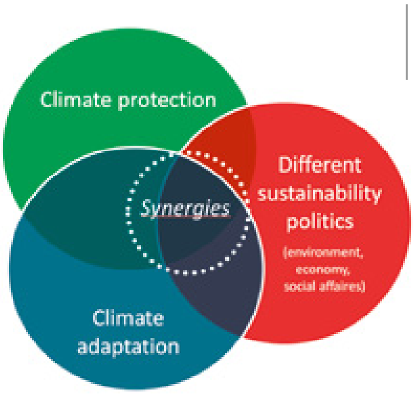

Fig. 7.1: Climate mitigation and climate adaptation can complement each other through synergies as with the thermal insulation of buildings or can be in conflict, such as air conditioning systems as climate adaptation measures in buildings. At the same time measures to improve carbon sequestration in forests or in urban green corridors must be coherently connected with the goals of biodiversity and urban development policies. In order to exploit synergies, integrated climate policies must fulfil a set of political coherence characteristics. (Figure: UFZ)

Global change with regional effects

The impacts of climate change show up at the regional level. Take Germany for example: under a scenario without any efforts towards climate protection („business as usual"), a temperature increase of between 2 and 3.5°C by 2100 must be reckoned with, depending upon the emission scenario and the type of climate model.

This warming will mainly affect the variability of precipitation and increase the frequency and severity of extreme weather events such as flooding and storms. However the forecasting uncertainties for these climate impacts are very high. Therefore, considerable modelling and monitoring efforts are still required to test and improve model forecasts, in order to arrive at more profound projection of regional climate change. This also applies to the ecological and economic impacts of climate change.
It particularly applies to the most vulnerable regions of this world such as Central Africa or many megacities around the world, where basic social and economic conditions, such as the level of education and disparities in income, make investigating and coping with the impacts from climate change more difficult.

Adaptation measures and their costs unknown to a large extent

The European Union with its adaptation strategy from 2009 started the process of getting member states to work out suitable strategies in various sectors and regions and to activate a process of political will in the respective European countries as well as at the level of the municipalities. However, suitable monitoring and indicator systems are still missing in order to control the success of such adaptation policies both effectively and on a regular basis, and to effectively coordinate adaptation policies between the European community, national governments, regions and municipalities. Building synergies and mitigating conflicts are therefore the magic formula of adapation polices for the near future. We will only be able to establish an effective adaptation strategy in the multi-level and multi-sector system of European communities, if legal, political and economic synergies are built with the objectives in the sectors and on the different levels and if conflicts are mitigated. Otherwise, we will be left with sheer declarations of intent. Here too, the EU can demonstrate global leadership qualities.

Fig. 7.2.a): Aggregated flood risk map for Leipzig. (Figure: Kubal, Haase, Meyer, Scheuer, 2009)

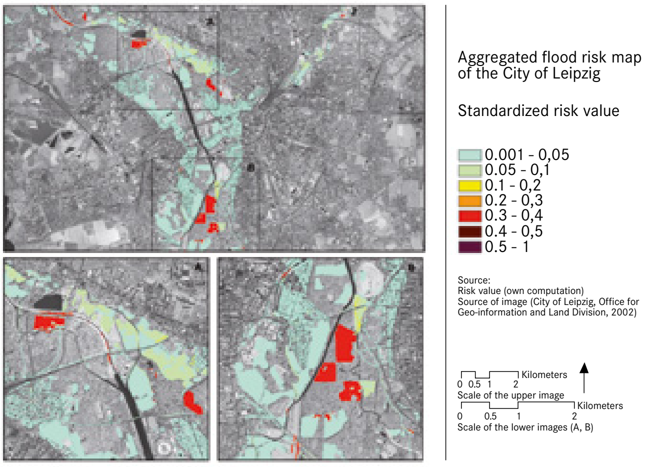

Fig 7.2.b.: Science (Prof. Dr. Christian Wissel, former director of the Department of Ecological Modelling at the UFZ) in discussion with stakeholders on the prospects of land use (Bielefeld 2005). (Photo: André Künzelmann)

Fig. 7.2: Decisions in the context of an integrated climate policy lead to risk trade-offs, which in the long run can only be decided upon as part of the discourse with stakeholders. Do we need new assessment bases for local drainage infrastructures in the face of increasing winter precipitation? How can fresh air corridors be designed to be socially compatible in heat-affected cities, so that established neighbourhoods are not destroyed? Socio-economic research can support these discourses through dynamic decision-support tools adaptable to local conditions, e.g. risk maps (Fig. 7.2a) and sustainability dialogues (Fig. 7.2.b).

While there are already numerous studies for estimating the costs of reducing greenhouse gas emissions and reverting to low carbon consumption, studies are missing to a large extent with regard to the costs of adapting to climate change. The available studies are mostly concerned with individual sectors e.g. agriculture, or with individual regions e.g. river catchment areas. In the sum of these individual studies, the various reciprocal effects in the economic system are not properly taken into account.

Integrated socio-economic concepts in demand

On the whole: In the socio-economic analysis of climate adaptation there are still large research gaps and considerable uncertainties, as there are so many different natural and socio-economic factors that need to be considered in context. This is the task of topic 7, i.e. the systemic research of regional climate change impacts in Germany and also the particularly vulnerable regions of this world. This topic is geared to establish concepts and regionalised strategies, through which the impacts of climate change can be mastered.

It should be the goal of all adaptation measures, to minimise the dangers of damage to ecosystems, human health and infrastructures. But which adaptation options do we have and which are suitable? How can synergies and conflicts be weighed up reasonably, in order to avoid any direct or indirect negative impacts of allegedly meaningful adaptation measures? For example: the extensive use of bioenergy as a strategy to reduce greenhouse gas emissions makes us more vulnerable to fluctuations in the climate, and thus increases social vulnerability in the long run. By contrast the saving of heating energy in buildings through thermal insulation serves at the same time mitigation and adaptation goals. Climate mitigation and climate adaptation are thus not opposed to each other. One without the other would anyway be insufficient.

Climate adaptation strategies however are coupled to the perception of the risks, and as such are embodied in the contexts of a regional-cultural society. Therefore, it is necessary to analyse the regional-cultural pillars of hazards, danger and risk, and to adapt clearly defined strategies of action for the respective societies. What we need is an integrated socio-economic climate mitigation and climate adaptation policy (Fig. 7.1).

Given the current level of economic knowledge, optimization of climate polices can only take place by means of an improved coordination between climate mitigation and climate adaptation as well as the integration of climate goals into environmental, economic and social policies. Policies are social strategies, which are based on a negotiation process, and as such they are culturally embedded. Conflicts between different policy goals and different stakeholders must be identified and minimized if possible. Regional-cultural perception research and the analysis of social discourse, which include studies of media impacts, are thereby of great significance. Risk perception and risk knowledge are the basic conditions, which form the prerequisite for adaptation and mitigation strategies. The investigation of innovative approaches of economic analysis of adaptation must therefore be coupled with socio-cultural analyses – both in their specific regional contexts (Fig. 7.2).

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The network of regional Helmholtz Climate Offices

Climate consulting: regionally specific, comprehensible, sound

Global climate change will have very different consequences in different regions. Climate change adaptation strategies must therefore take these regional differences into account, in order to, for example, avoid poor investments. Due to the growing need for consultation, the Helmholtz Association has developed a network of regional climate offices (Fig. 8.1).

The regional Helmholtz Climate Offices are integrated into the user-oriented climate research of the Helmholtz Association, which also includes research on climate protection, climate impacts and adaptation. Participants and decision-makers from politics, business and society thus receive regionally specific, clearly presented and sound climate information from them.

The Helmholtz Centres, which are active in climate and climate impact research, offer a wide range of climate-relevant research areas. The nationwide distribution of their locations and the existing technical networks allow good exchange of research results related to regional climate change and its consequences. The objective of the four regional Helmholtz Climate Offices is to bundle, concisely prepare and communicate research results on climate change for specific regions and natural areas. At the same time, the dialogue between climate research and the public is strengthened in the regions. The public‘s information needs are engaged and integrated into the research programmes of the centres.

Fig. 8.1: Network of regional climate offices of the Helmholtz Association. (Figure: Schipper, J.W., I. Meinke, S. Zacharias, R. Treffeisen, Ch. Kottmeier, H. von Storch, and P. Lemke, 2009, DMG Nachrichten 1-2009)
(GKSS: now Helmholtz-Zentrum Geesthacht, HZG)

The regional Helmholtz Climate Offices and their expertise

North German Climate Office	**Climate Office for Central Germany**	**South German Climate Office**	**Climate Office for Polar Regions and Sea Level Rise**
Helmholtz-Zentrum Geesthacht (HZG)	Helmholtz-Zentrum für Umweltforschung (UFZ) – Leipzig	Karlsruher Institut für Technologie (KIT)	Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI), Bremerhaven
Changes in storms, storm surges, ocean waves, and coastal climate	Climate change impacts and adaptation in the fields of biodiversity, hydrology, and society	Regional climate modelling and extreme weather events	Climate change related to polar regions and sea-level rise
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Each climate office represents the regional aspects of the climate research based on the scientific expertise of the respective Helmholtz centre. The basis for their expertise is further strengthened through the networking of the regional climate offices and cooperation with excellence initiatives, universities and state and federal agencies. In this way, regionally specific, sound climate knowledge can be communicated comprehensively within Germany.

Information from the corresponding climate-specific core competencies of the individual climate offices are exchanged and, where possible, transferred to the reference regions of the other climate offices. Informational material on specific topics and regional climate change will be developed jointly where possible. Supported by a coordinated external communication strategy (internet, conferences, workshops), the regional Helmholtz Climate Offices coordinate thematic inquiries.

Results from the REKLIM Helmholtz climate initiative are of particular interest for decision processes for adaptation strategies for climate change and emission reductions. The regional Helmholtz Climate Offices play an important role in communicating these results.

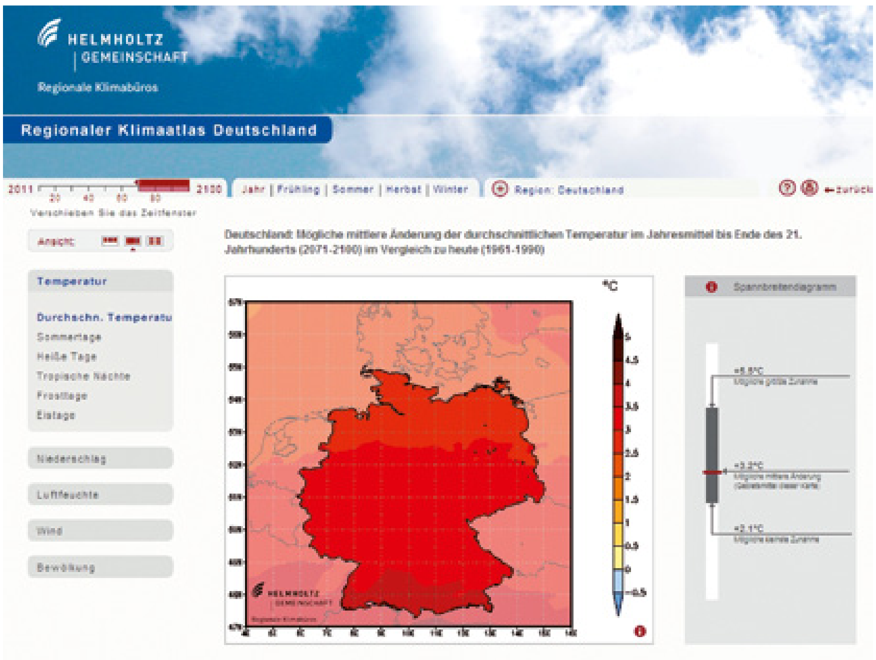

Fig. 8.2: An example of our work (screenshot of the website „www.regionaler-klimaatlas.de"): How the climate may change in the future in the various federal states is shown by the Regional Climate Atlas of Germany, which was developed by the four regional Helmholtz Climate Offices according to the model of the North German Climate Atlas. At www.regionaler-klimaatlas.de, possible future climate scenarios can be accessed publicly. In the climate map, decision-makers from climate-sensitive sectors, such as agriculture, tourism and energy supply, can take a look at predicted changes in temperature, precipitation and wind in various seasons in their federal state. With the Regional Climate Atlas of Germany, decision-makers in ministries and agencies are also provided with a scientifically sound basis for use in climate change adaptation strategies. (Figure: Meinke, I., E. Gerstner, H. von Storch, A. Marx, H. Schipper, C. Kottmeier, R. Treffeisen und P. Lemke, 2010, Mitteilungen DMG 02/2010)

AWI | DLR | FZJ | GFZ | HMGU | HZG | KIT | UFZ

Outlook

Climate research deals with a complex system, which requires interdisciplinary collaboration of scientists from physical, geological and biological disciplines. In the long run, the details of such a complex system will not be predictable. Therefore, the goal is to determine future averages and variances in all predictions and projections and to make realistic estimates for the occurrence of extreme events.

Here, the key challenge for REKLIM is to provide the necessary information, including the uncertainties in assessing future climate change and the required adaptations on a regional basis. This will be achieved through improved understanding of the climate-relevant processes with the help of innovative observation systems and optimised numerical models. The goal is to generate data for current and expected climate changes in various regions, to analyse these data to help improve global and regional climate models and to make the results available, through the regional climate offices, to the political decision-makers, the local governments, the business community and the general public.

Such regional forecasting is essential for adaptation measures. Adaptation alone, however, is not enough. An internationally coordinated mitigation strategy and its implementation are of even greater importance for the good of all nations.

Explanations | abbreviations

[1]*RESM*: **R**egional **E**arth **S**ystem **M**odel.

[2]*Aerosol*: Solid or liquid particles in the atmosphere. (The diameter of climate-relevant aerosols ranges from around 5 nanometres to several micrometres.) The main components of aerosols are sulphate, carbon, nitrate, ammonium and minerals. In the context of air pollution, aerosols of a certain size class (up to 10 micrometres) are known as fine particulate matter.

[3]*Ensemble simulation*: Multiple RESM simulations with modified initial and/or boundary conditions.

[4]*Parameterisation*: Simplified numerical description of a physical process based on empirical data. Due to the limited resolution of current models and the economics of computing time, in a complex chemical model, for instance, not all physical and chemical processes can be represented in detail, making parameterisation necessary.

[5]*Albedo*: Reflectivity of surfaces for incident radiation. The albedo is calculated from the ratio of reflected to incident light. Its value ranges between 0 and 1.

[6]*HIRHAM-NAOSIM*: Coupled regional Earth system model of the atmosphere (HIRHAM) and the ocean (NAOSIM).

[7]*Permafrost*: Ground that is frozen year-round (soil, sediment, rock).

[8]*HIRHAM-LSM*: Coupled regional Earth system model of the atmosphere (HIRHAM), the land surface and the soil (LSM).

[9]*COSMO-CLM*: **CO**nsortium for **S**mall Scale **MO**delling – **CL**imate **M**ode. Non-hydrostatic regional climate model. The consortium is a network of several European meteorological services.

[10]*COSMO-ART*: **CO**nsortium for **S**mall Scale **MO**delling – ***A**erosols*[2] and **R**eactive **T**race gases. Regional climate model with atmospheric *aerosol block*[2].

[11]*Satellite mission GRACE*: (**G**ravity **R**ecovery **A**nd **C**limate **E**xperiment). The twin satellites of the joint American-German mission GRACE provides a highly accurate global model of the static and time-variable components of the gravitational field of the Earth.

[12]*Thermohaline circulation*: This term is used for the ocean currents that are driven by the differences in density caused by temperature and salinity gradients. Together with the wind-driven currents, the density-driven circulation provides the mass and heat transfer within the oceans of the world, which is colloquially called the global ocean conveyor belt.

[13]*Ice-albedo feedback*: Ice reflects a large part of sunlight (high albedo), while the dark water surface absorbs a large portion of the radiation and converts it into heat. With the retreat of the bright ice surface in the polar ocean, more radiation is absorbed in the water and this heating leads to further melting of the ice. This cycle continues, forming a positive feedback loop.

[14]*TERENO*: **TER**restrial **EN**viromental **O**bservatories www.tereno.net

[15]*Radio occultation*: Special measurement alignment of two satellite sensors at which the change of a radio signal during the penetration of the atmosphere is observed. Due to the satellite orbits of the transmitter and receiver, an average vertical profile of the atmospheric density and water vapour can be generated.

[16]*Proxy data*: Indirect climate indicators, such as tree rings, pollen, varves, ice cores, sediment cores, etc.

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