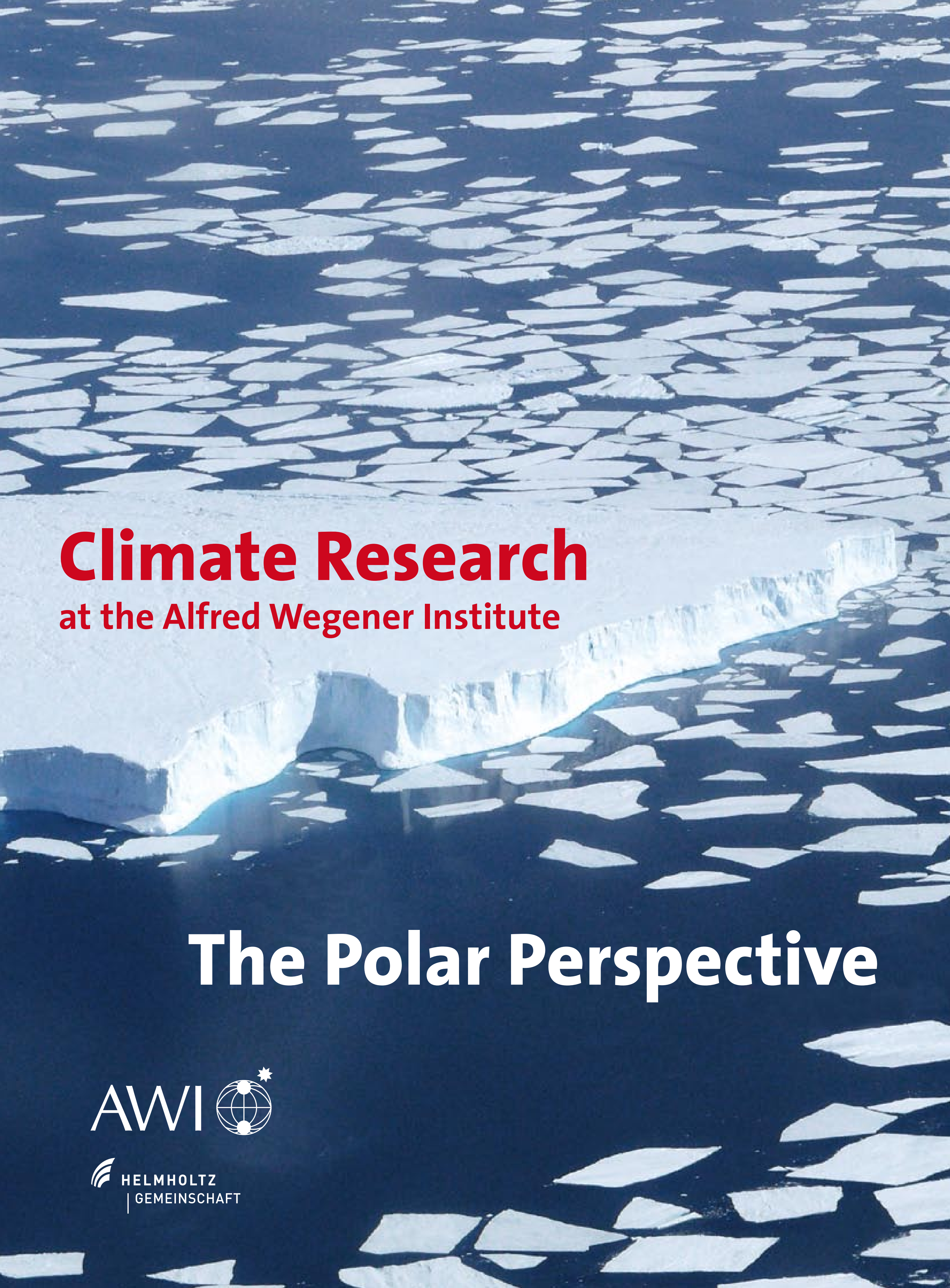


Climate Research

at the Alfred Wegener Institute

The Polar Perspective

AWI

HELMHOLTZ
GEMEINSCHAFT

Tabular icebergs are a typical phenomenon in the Southern Ocean. The ice sheet is growing at high altitudes in the interior of Antarctica due to snowfall, a process in which the ice masses very slowly move outward to the ice shelf areas, which then increase in size, become unstable and as a result shed off large tabular icebergs. In a state of equilibrium the growth in the interior of Antarctica and the loss due to calving of icebergs on the edge balance each other out. However, more recent observations show that the ice losses in the Antarctic are increasing, the ice sheet is shrinking and therefore the sea level is rising. This also applies to the Greenland ice sheet.

Contents

The photo shows a group of scientists on a sea ice floe carrying out physical and biological investigations in sea ice. Sea ice is a porous medium that contains a rich and diverse ecosystem in hollow spaces of varying size. An aspect of scientific interest is how the ecosystem has adapted to the extreme physical conditions in sea ice and how it changes in the process of climate warming.

Preface

The Earth is undergoing profound climate change. The last report of the Intergovernmental Panel on Climate Change (IPCC) of 2007 shows, on the one hand, that climate change is advancing extremely rapidly and, on the other hand, that most of the warming of the past 50 years is very likely anthropogenically induced. Particularly the polar regions are very sensitive to even slight climate changes and therefore play a paramount role for the global climate system.

The Alfred Wegener Institute for Polar and Marine Research in the Helmholtz Association in Bremerhaven commenced its work in July 1980. Since then it has numbered among the leading institutions for polar research worldwide and has made significant contributions for international Earth system and climate research in the polar regions and coastal waters. As a Helmholtz Centre, it supports the mission of the Helmholtz Association in developing solutions for major scientific challenges of relevance to society. Observations of temperature changes in the polar regions indicate a warming process in the Arctic and on the Antarctic Peninsula that is proceeding at double the pace of the global average. This rapid warming not only affects the polar regions, but has worldwide impacts. The melting of the ice sheet in Greenland and in the West Antarctic accelerates the rise in sea level and thus changes on all coasts, the decline in sea ice influences the global climate, the loss of permafrost regions alters entire landscapes and releases climate gases, and profound changes in the polar ecosystem can be expected as a consequence.

Stopping or at least slowing down climate change with its far-reaching and regionally varying consequences for humanity and nature is one of the greatest challenges of the 21st century. Whether we are able to adapt in time to the imminent changes will largely depend on whether the results from research and science are communicated to an adequate degree.

This brochure will provide you with an overview of some of the topics AWI is working on in the field of climate research in polar regions. I hope you enjoy reading it.

Prof. Dr. Karin Lochte
Director

Prof. Dr. Peter Lemke

Our climate from the polar perspective

Climate fluctuations are a major feature of the Earth. They are documented by direct measurements, chronicles and biological/geological archives in tree rings, corals, ice and sediment cores. Climate fluctuations take place on time scales ranging from weeks to millions of years, though the present state of the climate is the result of a continuous development lasting 4.5 billion years. A large number of pronounced climate fluctuations with very visible consequences have occurred in the course of the Earth's history and they have always been a challenge for life on the Earth – and certainly for humankind as well. Impressive examples include the past ice age cycles, during which large portions of the northern continents were covered at times by expansive ice sheets and the sea level in interglacial periods was a few metres higher than today, as compared to around 120 metres lower during the ice ages.

Climate fluctuations are a key element in the evolution of the Earth and they will continue to occur in the future, too. In the past climate fluctuations occurred as a result of natural processes. They were a consequence of external forcing (changes in the parameters of the Earth's orbit, volcanic eruptions and small changes in solar radiation) and internal interactions in the climate system, comprising the atmosphere, ice masses, oceans, land surface and all forms of life on the continents and in the sea.

Since recently humanity has been in a position, because of the immense rise in the world population and rapid technological development, to actively and effectively impact on climate variations. The global warming of the past 50 years, for instance, has been human-induced for the most part, in particular by virtue of the constantly increasing emissions of carbon dioxide due to the intensive use of fossil energy sources and changes in the land surface caused by agriculture, industry and settlement. As a result of this anthropogenic climate change, a significant rise in global warming of around 3 °C is expected in the next 100 years. Detailed studies on the physical causes of climate fluctuations and the response of the climate system to human impact are currently the subject of national and international climate research (World Climate Research Programme, http://www.wcrp-climate.org). The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (http://www.ipcc.ch) provides an up-to-date summary of current knowledge on the climate system.

A better understanding of the climate system is absolutely necessary for adaptation and mitigation measures. Climate events on the Earth come about as a result of interactions between the atmosphere, ice, oceans and land surface. The Earth is heated in the tropics and cooled at the poles. The temperature contrast between the poles and the equator triggers wind and oceanic currents with the Earth, acting as a gigantic heat engine that transports heat from the tropics to the poles. This transport is controlled by a large number of feedback loops. At the same time processes in the polar regions play a decisive role. Changes in the polar regions influence the energy balance of the Earth, the gas composition of the atmosphere, ocean currents, wind systems and the sea level.

These complex interrelationships give rise to a number of questions for our research sectors.

What is the connection between the development of our climate and the interaction between the atmosphere, ice, oceans and land surface in the polar regions and how do human impacts and natural climate fluctuations influence each other?

How does the atmosphere communicate with the ocean through a broken sea ice cover? What are the key processes in the pronounced decline of sea ice in the Arctic and what can be said about changes in the thickness of sea ice?

How do the polar regions influence the production and spread of deep water and thus global ocean circulation?

What is the optimal modelling of oceanic circulation and its impact on the climate system?

How great are the losses in the continental ice masses (particularly of Greenland) and how does the sea level react to melt water and warming?

What are the causes of the big changes in permafrost in the Arctic and what immediate and long-term effects do they involve?

What information from biological/geological climate archives can be used for an understanding of the climate system?

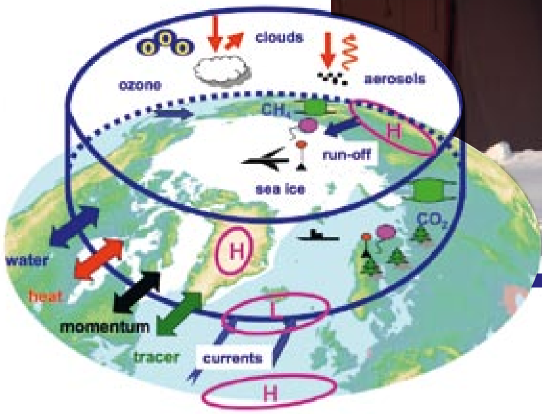
How can we utilise these data to optimise climate models and project future climate development?

What role does plankton in the ocean play in the climate system?

And finally, what impacts do the processes in polar regions have on the climate in Europe and on other parts of the globe?

To answer these fundamental questions for the climate – and humanity – the Alfred Wegener Institute undertakes ship expeditions with the research icebreaker 'Polarstern' and carries out aircraft-based measurement programmes as well as overland expeditions. Our researchers make use of these detailed observations and process studies to develop optimised coupled climate models that point out how altered conditions in the climate system have a regional and local impact. And last but not least, scientifically sound data and AWI scenarios serve to provide advisory support to the political and economic arena, authorities and the broad public in decisions on regional development.

Fig 1: Schematic diagram of the research fields
(Figure: Klaus Dethloff, AWI Potsdam)



Improved understanding of Arctic climate changes through measurements and modelling

The Arctic plays a key role in the global climate system. The snow and ice predominantly covering the Arctic are two factors responsible for this. They exert a strong influence on the surface energy balance and thus also on the global circulation of the atmosphere and the ocean. The Arctic climate has undergone significant changes. The most obvious of them is the decline in the sea ice cover in recent decades.

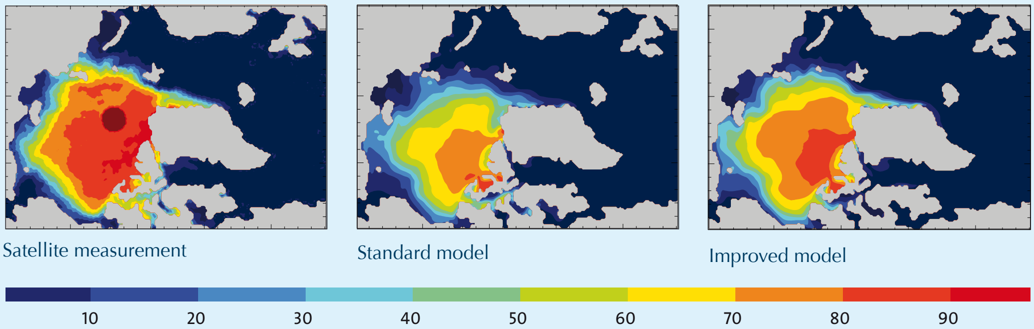
Both the anthropogenically reinforced greenhouse effect and the natural variability of the processes in the Arctic have contributed to this. The variability results, among other things, from complicated feedbacks in the atmosphere-land-ice-ocean system involving ice, clouds, water vapour, aerosols and ozone. A combination of measurements under Arctic conditions and computer simulations (models) is necessary to research these factors.

Climate dynamics

Simulations with Earth system models still display a high degree of uncertainty in assessing future climate changes in the Arctic and thus also in determining the extent to which Arctic processes contribute to global climate change.

The regional climate model developed at AWI is used to understand and quantify climate variability and climate changes in the Arctic. This is done in connection with an analysis of measurement data from ground stations, radiosondes, aircraft and satellites. Furthermore, we applied such a regional climate model to analyse atmospheric measurements that an AWI member carried out at the Russian station NP-35 while it was drifting on Arctic sea ice for several months. On the basis of the measurement results, AWI scientists have improved the mathematical and physical descriptions of small-scale processes contained in the model. In addition, they integrated a regional coupled atmosphere-ice-ocean-climate model over a period of several decades in order to understand changes in the Arctic summer sea ice in the past 60 years. To simulate sea ice anomalies realistically, the atmospheric and ocean circulation, winter ice growth as well as the ice-albedo feedback have to be described correctly.

The regional process studies contribute to improve the global Earth system models. These results will be included in the coming IPCC report and help society to prepare for future environmental changes.



(Figure: Wolfgang Dorn, AWI Potsdam)

Fig 2: Mean sea ice cover

in September of the years 1988 to 2000 [in percent of the area] from satellite measurements (SSM/I data) and two simulations of the coupled regional climate model HIRHAM-NAOSIM. Compared to the standard version of HIRHAM-NAOSIM (centre), the improved version (right) contains a new, far more complex description of the interactions between the atmosphere and sea ice. This results in a more realistic representation of the ice-albedo feedback that is important for the summer decline in sea ice, thus reducing the deviations of the model from the satellite measurements.

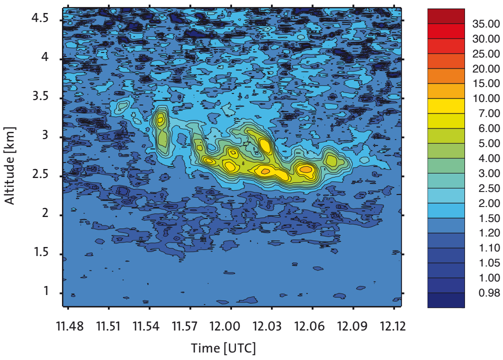


Fig 3: Subvisible ice cloud

Observation of a subvisible ice cloud by means of aircraft-borne Lidar near Spitsbergen (Arctic) on 10 April 2007. The colour-coded backscatter ratio shows the vertical and horizontal extent of the cloud. Subvisible ice clouds have a significant influence on the radiation balance, particularly during the polar night. A more strong backscatter of the cloud translate into a more intensive colour (yellow, orange).

(Figure: Astrid Lampert, AWI Potsdam)

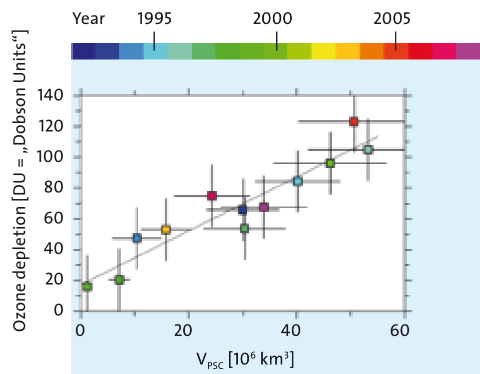


Fig 4: Chemical ozone depletion in twelve winters

The horizontal axis represents the geographical extent of conditions favourable for the existence of so-called polar stratospheric clouds (PSC) in each winter. These clouds play a key role in the ozone depletion process. The colder the stratosphere is, the more widespread is the formation of these clouds. The diagram shows how anthropogenic ozone depletion is modulated via the natural year-to-year variability of the stratospheric temperatures and the resulting variability of the PSC extent. The measurements make it possible to empirically quantify the relation between stratospheric temperature changes and ozone depletion and thus contribute to more reliable forecasts of future ozone losses in climate change scenarios.

(Figure: Markus Rex, AWI Potsdam)

Tropospheric aerosols

Aerosols in the Arctic troposphere influence the radiation balance and the characteristics of Arctic clouds. Extensive measurements are carried out in order to be able to represent these effects in climate models in an optimal way. AWI researchers have conducted a number of airborne measurements in the central Arctic together with US and Canadian institutions for this purpose. They determined aerosol distribution and meteorological parameters in vertical and horizontal cross-sections, placing special emphasis on the atmospheric boundary layer.

To study the Arctic atmospheric boundary layer, AWI scientists at the German-French Arctic research base AWIPEV on Spitsbergen set up a mobile light radar (Lidar), tethered balloons and energy flux measurement systems. Vertical aerosol, ozone and greenhouse gas profiles are determined from a special atmospheric observatory at the AWIPEV base. Meteorological observations supply data on the most important parameters to identify climate changes. These measurements are carried out continuously throughout the year.

Stratospheric ozone

Chemically induced disturbances of the ozone layer in polar regions are one of the strongest indications of changes in the atmosphere. At least in the Antarctic, changes in the ozone layer make a substantial contribution to the general development of climate. It is necessary to gain a better understanding of the role of the polar ozone layer in the climate system in order to allow for more reliable assessments of future climate change. AWI uses measurements and models of atmospheric processes in polar regions for this purpose. For instance, AWI Potsdam has detected and precisely quantified considerable chemical ozone losses in the Arctic stratosphere by coordinating international measurement campaigns in which approximately 40 measuring stations were involved ('match method'). The institute was able to isolate the anthropogenically induced fraction of the ozone loss from the natural ozone variability. The now long-term series of these measurements makes it possible to examine the connection between climate changes and ozone losses over the Arctic and to determine the sensitivity of ozone to temperature changes.

Modelling that follows the air masses is used to study the reactions involved in chemical ozone depletion with the help of measurement data from the stratosphere. This method is a valuable complement to the measurements in the laboratory used to date.

Fig 1: Sea smoke over a partially ice-covered ocean. Sea smoke can form when much colder air flows over warm water.
Photo: Jörg Hartmann, AWI

Physical processes in the polar atmosphere

The climate, i.e. the typical weather pattern over longer periods of time (e.g. 30 years), including its variability, results from the interplay between many individual processes in the Earth system in combination with solar and terrestrial conditions. Such processes in the atmosphere include the formation of clouds and precipitation, radiation transfer and vertical exchange of heat, mass and momentum.

Fig 2: AWI's research aircraft 'Polar 5' in operation in the Antarctic.
Photo: Gerit Birnbaum, AWI

AWI scientists investigate physical processes in the polar troposphere, including the interactions between atmosphere, sea ice and ocean, placing the focus on processes with spatial dimensions of approx. 1 to 50 km. An example of a phenomenon in the polar atmosphere in which the above mentioned processes are relevant is sea smoke over partially ice-covered ocean, as can be seen over the ice-free leads in Fig. 1.

To study these processes, AWI researchers collect data on expeditions as well as at observatories over a period of decades, observe large regions using remote sensing methods, develop physical mathematical models of the atmosphere and in this way simulate weather developments as well as examine the quality of model data records for polar regions by means of in-situ measurements. Compiling and interpreting many physical details serve the purpose of better understanding short-term processes and developing methods by means of which the impacts of such processes can be taken into account better in large-scale models.

Two of our research topics are presented here.

The first topic is the study of the interaction between ice, ocean and atmosphere over Antarctic sea ice. In February and March 2010 AWI scientists carried out an aircraft campaign over the Weddell Sea in Antarctica in cooperation with the British Antarctic Survey (BAS). Some flights took place far in the south over the Ronne polynya region, where very few atmospheric measurements had previously been available. This region is important because the pack ice is pushed to the north by the downward flow of cold air from the adjacent ice shelf so that an area up to 100 km wide, which is initially ice-free and later covered only with thin ice (polynya), can develop along the ice shelf. For this mission the 'Polar 5' (Fig. 2), AWI's research aircraft, was equipped with special meteorological instruments capable of measuring parameters, such as wind, air temperature, moisture content, ice and water surface temperature, etc., very precisely at a high scan rate.

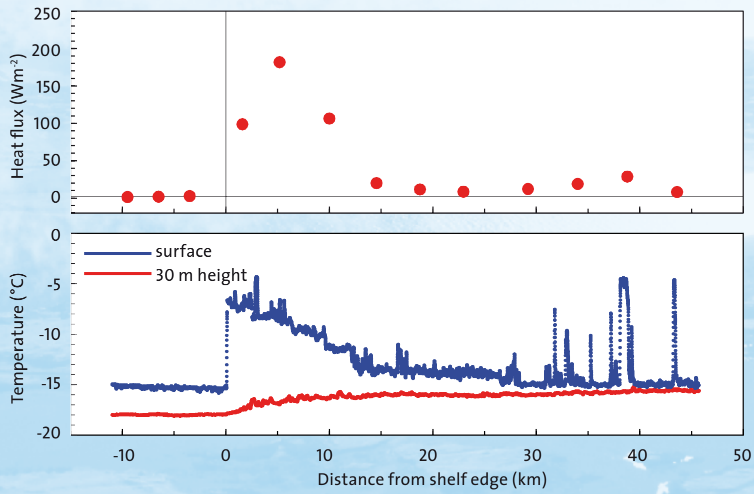
These high-frequency measurements permit, for example, calculations of heat fluxes between atmosphere, ocean and sea ice. The first evaluation of the data obtained shows that the ocean over the polynya emits heat of up to 200 watts/m^2 into the atmosphere (Fig. 3). We were also able to measure clear signals of the heat flux above the numerous ice-free leads observed north of the Ronne polynya. We use the data to check our process models that enable us to calculate, for instance, interactions between the atmosphere and the sea ice or the ocean above such leads. Thus, the combination of measurements and modelling makes it possible to develop methods for recording small-scale processes above the leads in weather forecast and climate models better than those to date.

The second topic involves precipitation, a major parameter for characterising weather and climate. In polar regions precipitation measurement is particularly difficult and thus only a very few measurements are available. For this reason great importance is attached to precipitation modelling. In this connection we at AWI use the German Meteorological Service's high-resolution weather forecast model COSMO, which has been adapted to Antarctic conditions, for case studies. In this way we are able to obtain information on the spatial and temporal variability of precipitation. Fig. 4 shows the simulated precipitation distribution over Queen Maud Land in Antarctica for a period of several days as an example. The weather was characterised by several low-pressure systems passing through whose fronts brought precipitation far into Queen Maud Land. The distribution of precipitation is greatly influenced by the respective path of the front, but also by the rise to the Antarctic plateau. On the plateau, where these effects are weaker, you do not see a monotonous decline in precipitation towards the inner Antarctic in Fig. 4. There are indications that the wave motion of the air initiated by the mountain range triggers secondary precipitation cells.

Improvement of the methods to describe clouds and precipitation as well as simulation of precipitation distribution, including evaluation, are other major research topics.

Fig 3: Heat fluxes and temperatures

Heat fluxes and temperatures that were measured during a flight with 'Polar 5' across the Ronne polynya on 20 February 2010. The flight first followed a course from south to north at a low elevation over the ice shelf, then across the polynya and further over the adjacent pack ice. Peaks in surface temperature indicate leads. At the time of this measurement flight the polynya was only about 25 km wide.
Figure: Christof Lüpkes, AWI



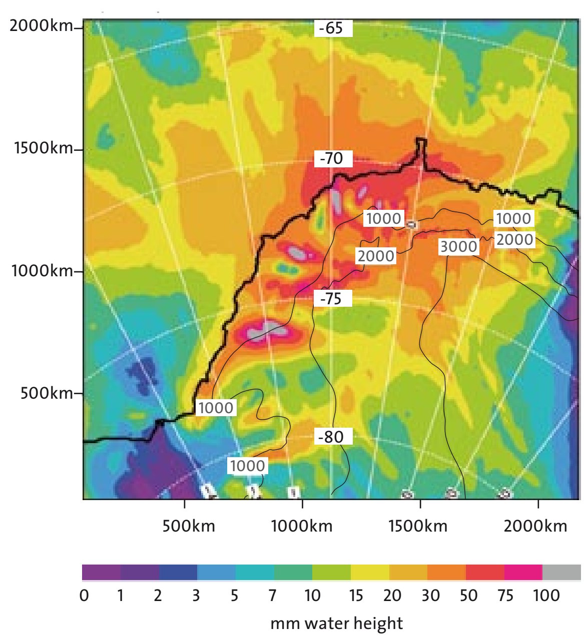


Fig 4: Simulated horizontal distribution of precipitation amounts (in mm water height) for the period from 2 to 12 February 1999. Use of the COSMO model of the German Meteorological Service.
Figure: Ulrike Wacker, AWI

Launch of an ozonesonde from the balloon filling station on the roof of 'Neumayer Station III'

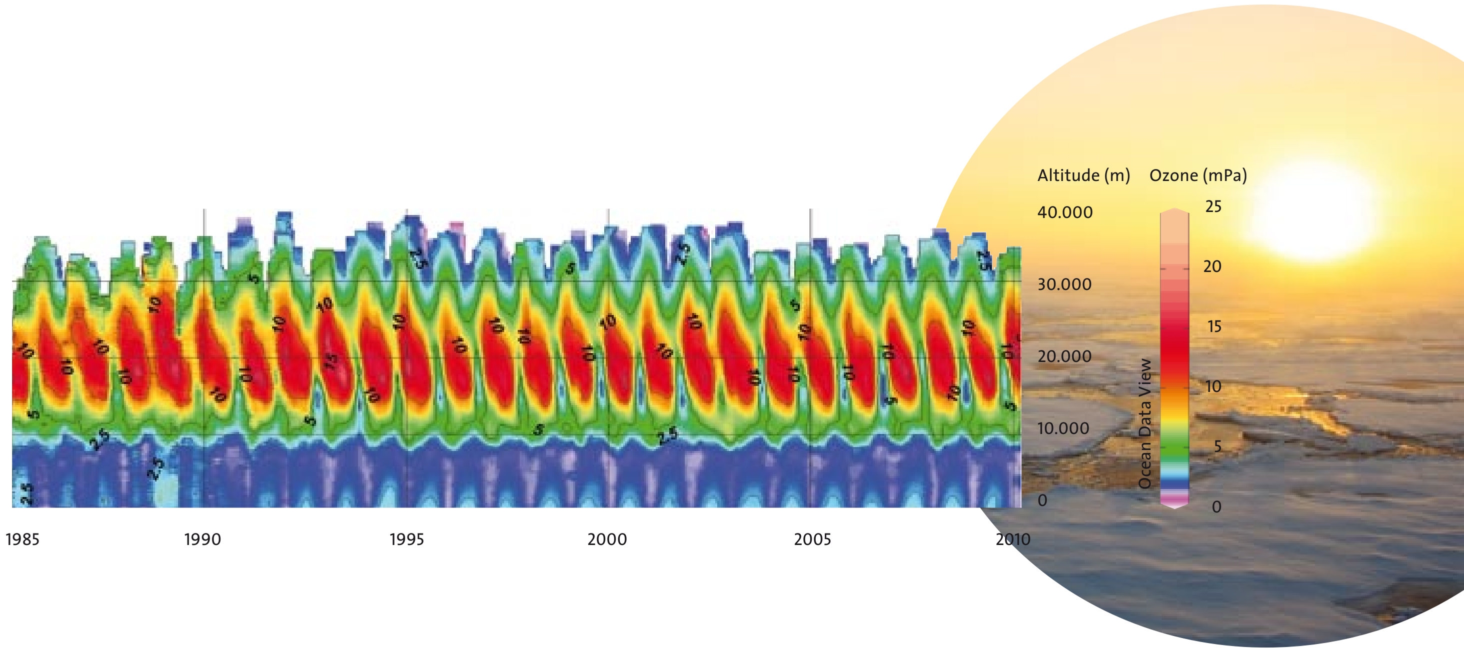
Long-term measurements show: ozone layer above the Antarctic has not yet recovered

The ozone hole above the Antarctic was discovered in 1985. The presumption that chlorofluorocarbons (CFCs) from refrigerators and spray cans damage the ozone layer had already been a subject of discussion among experts for a long time. However, a measurable decline in the ozone layer was found for the first time in the Antarctic, of all places, far away from all anthropogenic CFC sources on the Earth.

This discovery turned out to be of great significance far beyond the Antarctic since it led to the Montreal Protocol in 1987, in which the signatory states agreed to complete elimination of ozone-destroying substances. At the same time as the discovery of the ozone hole at the British Antarctic station Halley, ozone measurements by means of weather balloons started at the 'Georg-Forster station' operated by the German Democratic Republic. After reunification of the two German states Neumayer station took over this measurement programme and has continued it down to today on a continuous basis. Both stations are located in Queen Maud Land in the Antarctic at a latitude of approx. 70° S. Their measurements form a unique continuous time series now lasting over 25 years: a record in the Antarctic!

Weather balloons are released into the atmosphere every day at Neumayer. The rubber balloons filled with helium reach an altitude of up to 37 km within approx. 2 hours before they burst. A small radiosonde attached to the balloon measures the temperature, moisture and wind during this time. An exceptionally large weather balloon that carries an ozonesonde in addition to the radiosonde is used once a week.

Such measurements are expensive and elaborate. In contrast to optical methods, which usually only show the total ozone of the entire air column above a measuring site, ozonesonde provide an altitude resolution of the ozone profile of approx. 25 m. This makes it possible to study the dramatic changes taking place in the ozone layer during the Antarctic spring.



As shown in Figs. 1 and 2, the dramatic ozone depletion is restricted to certain altitudes (15 to 18 km) and seasons. In the last 25 years the mean ozone partial pressure in the Antarctic spring (September to November) has declined (Fig. 3). Whereas the mean values for the ozone layer were around 6 mPa in the 1980s, only half of that has been measured in recent years. At the same time the temperature at this altitude and in this season also changed.

A large part of this trend is attributed to chemical ozone depletion due to anthropogenic CFCs. However, dynamic processes are also discernible. In 1988 as well as in 2002, for example, a collapse of the stratospheric circumpolar vortex over the Antarctic enabled warm and ozone-enriched air to flow from the lower latitudes to the area above the Antarctic.

Although the Montreal Protocol has very successfully stopped the production of CFCs, measurements at the 'Neumayer station' do not yet indicate a recovery of the ozone layer. However, regeneration of the ozone layer is expected in the coming decades. Neumayer will continue to play a major role in research on this process since the construction of the new station facility, completed in 2009, ensures the continuation of these measurements.

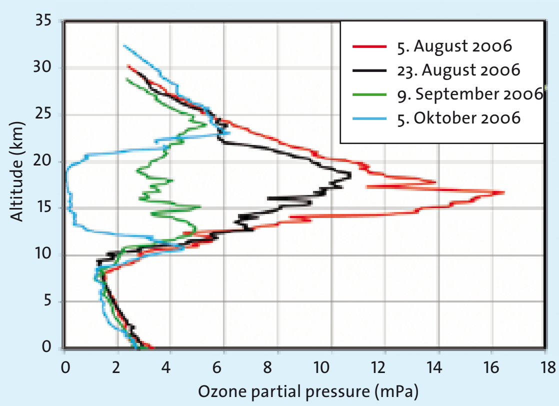
Fig 1: Time-altitude section of ozone partial pressure above the Antarctic stations Georg-Forster and Neumayer. The ozone layer lies at altitudes between 10,000 and 25,000 m, identifiable by the high ozone values shown in yellow and red. During the Antarctic spring between September and November the ozone layer regularly weakens, displaying local minimum values in some years (blue) instead of maximum values (red).
Figure: Gert König-Langlo, AWI

Fig 2: Ozone altitude profiles

Ozone altitude profiles, measured above 'Neumayer station'. The dramatic ozone destruction in the Antarctic spring led to the complete depletion of the ozone layer in October 2006.
Figure: Gert König-Langlo, AWI

Fig 3: Time series

Time series of the average ozone partial pressure (red) and temperature (blue) from September to October 15 to 18 km above the Georg-Forster and Neumayer stations.
Figure: Gert König-Langlo, AWI



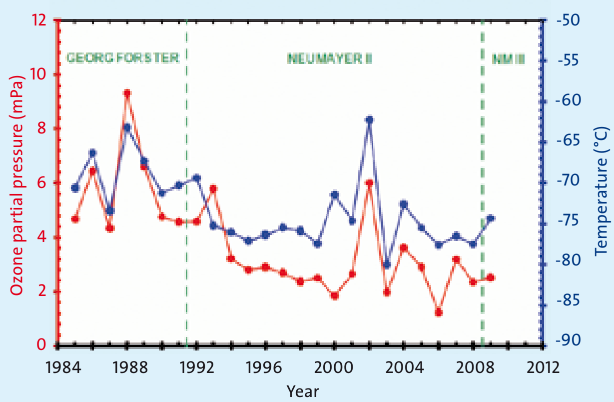


Fig 1: Towed sensor for determining the thickness of sea ice on the fuselage of the polar research aircraft 'Polar 5' in Fairbanks, Alaska
Photo: Stefan Hendricks, AWI

Decline in Arctic sea ice causes anomalies in ocean and atmosphere

The area in the Arctic Ocean covered by ice varies seasonally and reaches its minimum in September. In this month the ice-covered area has declined by 11 % a decade on average since the beginning of satellite measurements. While 7.5 million km^2 of the Arctic Ocean were typically covered by ice at the beginning of the 1980s, the figures in recent years have been around 5 million km^2 after a drastic decline to 4.3 million km^2 occurred in 2007.

Because of its key function in the climate system as an intermediary between ocean and atmosphere and as a transport medium for freshwater, these changes are alarming. Changes in Arctic sea ice manifest themselves in the oceanic and atmospheric circulation. Furthermore, substantial impacts on ecosystems in the Arctic and human activities can be expected there.

The summer ice cover does not diminish continuously, the trend is subject to considerable fluctuations from year to year. Many of these fluctuations are due to the wind. In the long term, however, the ice cover and the processes that determine the ice volume in the Arctic Ocean are decisive. As long as the ice thickness remains above a critical value in large sections of the Arctic Ocean, the ice will not completely melt in summer. At the end of the summer sea ice of small thickness is sufficient to insulate the oceanic covering layer from the atmosphere and extensively reflect the insolation. If the ice thickness drops below this critical value, however, the thermodynamic effects are enough to make large sections of the Arctic Ocean ice-free towards the end of summer.

Arctic-wide ice thickness measurements are available only to a minimal extent at present. Previous measurements carried out by submarines do not cover the entire Arctic Ocean and assessments of the change in ice volume may be distorted due to redistribution of the ice to the areas not covered. However, a significant decline in the ice volume since the 1960s is an undisputed fact. AWI has recorded the ice thickness in the region north of the Fram Strait and in the western Arctic by means of electromagnetic (EM) measurements from helicopters and aircraft (Figs. 1 and 2). This may not enable area-wide observation, but these measurements will play a major role in the calibration and validation of future thickness measurements via satellite.

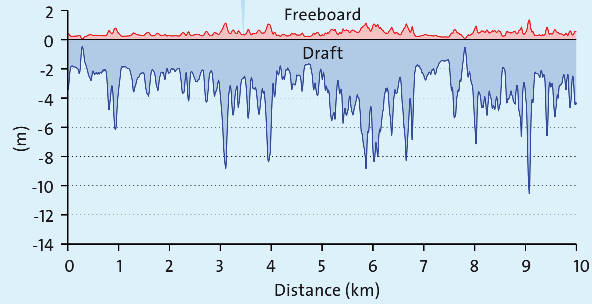
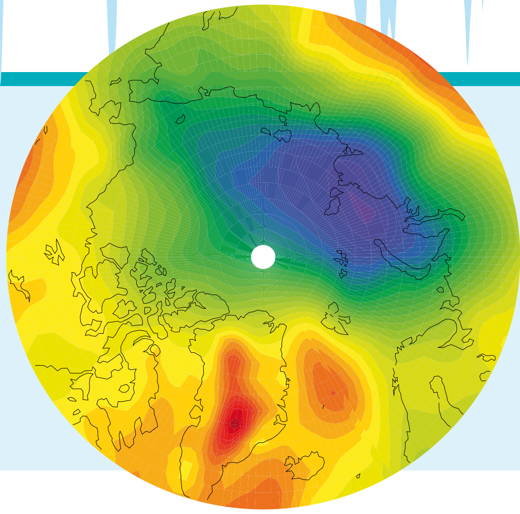


Fig 2: Ice thickness profile

Ice thickness profile in the Arctic Ocean, measured with the EM-Bird in spring 2009. The ice thickness is composed of the portion of the ice below (draft) and above the water surface (freeboard).
Figure: Stefan Hendricks, AWI



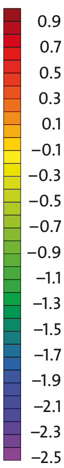


Fig 3: Anomaly of the ground air pressure (in hPa) from July to September due to ocean surface temperature and ice anomalies, as they occurred in summer 2007. A pronounced low-pressure anomaly of up to 2 hPa can be seen over the Siberian shelf seas.
Figure: Jonas Blüthgen, AWI

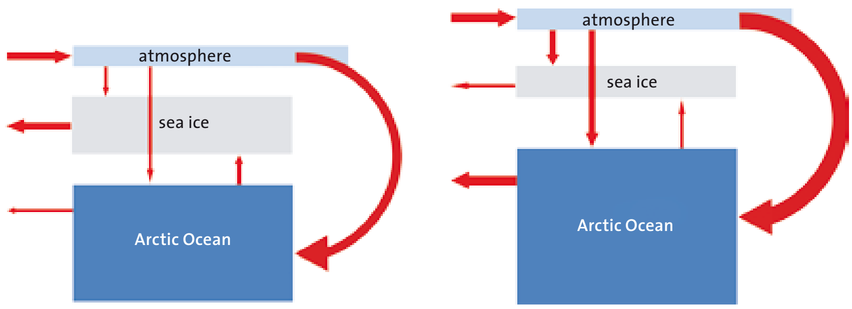


Fig 4: Schematic diagram of the freshwater balance of the present-day Arctic Ocean (left) and the freshwater balance expected in the future (right). The red arrows indicate the direction and intensity of freshwater transport between the reservoirs (atmosphere, sea ice, ocean) and the exchange with lower latitudes. The volume of freshwater diminishes in sea ice, but increases in the Arctic Ocean.
Figure: Rüdiger Gerdes, AWI

The substantial ice anomalies in the past summers give rise to the question of their impacts. Model simulations regarding the impacts of the anomalies in 2007 in terms of sea ice concentration and ocean surface temperature show a low-pressure anomaly over northern Siberia and a high-pressure anomaly over Canada and Greenland (Fig. 3). Overall, there is a perceptible trend towards more meridional winds (that are essentially oriented parallel to the meridians, i.e. either in a south-north direction or vice versa) and thus possibly to greater fluctuations in air temperature also at mid-latitudes. Moreover, there are indications of mutual reinforcement of sea ice and wind anomalies.

The Arctic Ocean takes up freshwater from rivers that drain Asia north of the Himalayas. It thus receives a proportion of the total mainland runoff that is far greater than the area of the Arctic Ocean in relation to the global ocean. In equilibrium the Arctic Ocean has to export just as much freshwater as flows into it from the various sources. The southward transport of sea ice containing little salt through the Fram Strait is a major sink for freshwater in the Arctic Ocean.

In future we can expect more precipitation over the Arctic Ocean and an increased mainland runoff to such an extent that the Arctic Ocean will receive even more freshwater than to date. At the same time the sea ice declines in terms of area and volume and thus the export of sea ice through the Fram Strait declines as well. In equilibrium, therefore, significantly more freshwater has to be transported across the ocean to the south than previously. In an adjustment phase a decrease in the mean salt concentration may take place in the Arctic Ocean (Fig. 4), which would have consequences for the regional sea level and the exchange with the European Arctic Ocean.

HAFOS records long-term changes in the ocean

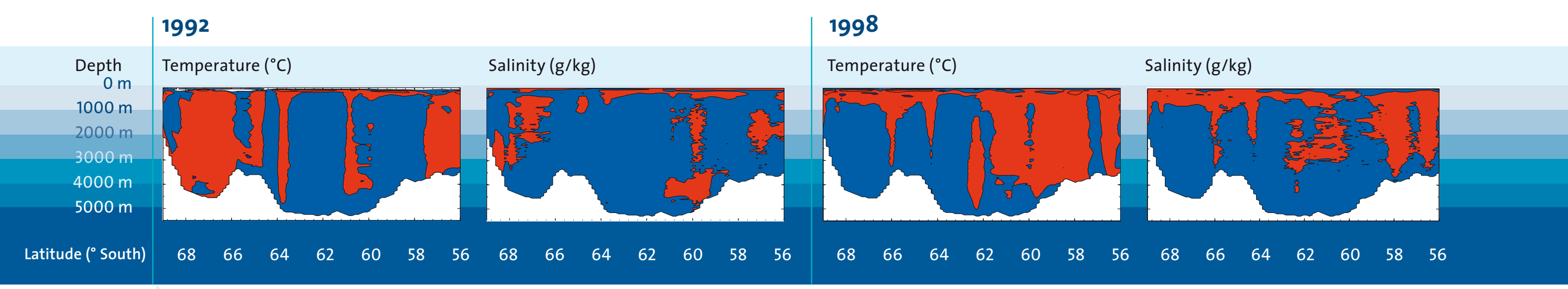
The polar oceans have a triple effect on the climate system. They represent a colossal heat store that buffers changes in the atmosphere; via sink and upwelling processes they control global circulation, which involves heat transport from the lower to higher latitudes; and they influence the global radiation balance via interaction with sea ice.

Fig 1: The warming (left) and increase in salt concentration (right) in the Atlantic sector of the Southern Ocean from 1992 to 2008, measured along the Greenwich Meridian. Red areas are warmer and have a higher salt concentration than the average while blue areas are colder with a lower salt concentration. Temperature and salt concentration have risen significantly during this period.
Figure: Gerd Rohardt, AWI

Biogeochemical and physical processes exert extensive influence on the ocean as an ecosystem whose condition has an impact on use of the living resources as well as on the CO_2 concentration of the atmosphere.

An investigation of these processes entails measurements in the ocean. On the one hand, relatively short process studies take place in this connection while, on the other hand, the measurement of climate processes requires long time series that can only be maintained by setting up measurement systems. Such efforts are summarised in the HAFOS project (Hybrid Arctic/Antarctic Float Observing System). HAFOS is a contribution to the Arctic and Southern Ocean Observing System supported by international organisations like the World Climate Research Programme (WCRP). The aim of these international observing systems is to enable measurements providing sufficient temporal and spatial coverage and making it possible to record long-term changes in the ocean.

This is necessary in order to analyse the extent to which the discernible changes are triggered by natural and/or anthropogenic causes. Biogeochemical changes play an increasing role and should also be taken into account. Since natural and anthropogenic causes can only be clearly separated in a model, model validation and



improvement through long-term measurements are indispensable to achieve this goal. HAFOS contributes to establishing these globally based systems in the polar oceans, too. To examine the impact of the ocean as a heat store, it is important to know whether and how the warming effect reaches the deeper water layers (Fig. 1).

Natural systems are subject to numerous fluctuations that we can correctly identify only with sufficient resolution. For this reason ship-based measurements with variable time intervals (up to several years) are not an adequate basis for diagnosing long-term changes quantitatively. Rather, they have to be complemented with quasi-continuous measurements at key points using autonomous systems (Fig. 3). Changes lasting years to decades take place in spatially complex movement patterns. Local measurements therefore have to be supplemented by large-scale/extensive data acquisition.

For local measurements having a high degree of accuracy and temporal resolution we use anchored devices holding different sensors. Area-based measurements are carried out by means of so-called floats, i.e. freely drifting platforms that submerge and surface in the ocean in order to measure vertical profiles. The data are transmitted via a satellite link. Under the ice the position is determined using sound sources in the moorings. In the Arctic ice platforms carrying vertically profiling devices on a wire are used because of the longer lifetime of the sea ice. Controllable measuring platforms, so-called gliders, also take vertical profiles, but they are set up to move horizontally on a specified measurement course. AWI plans to carry out ship-based measurements in the Southern Ocean, Arctic Ocean and Fram Strait using moorings, floats, ice platforms and gliders within the framework of HAFOS (Fig. 2).

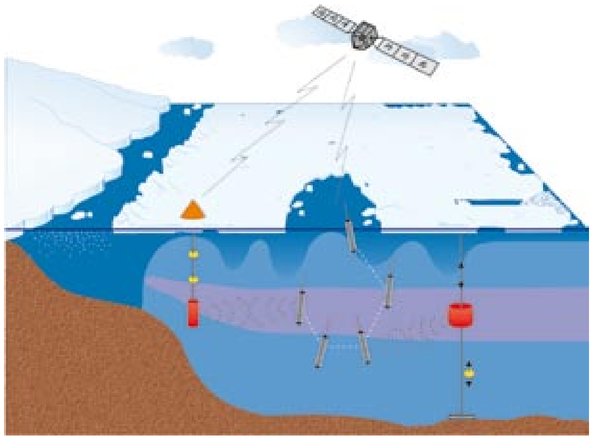
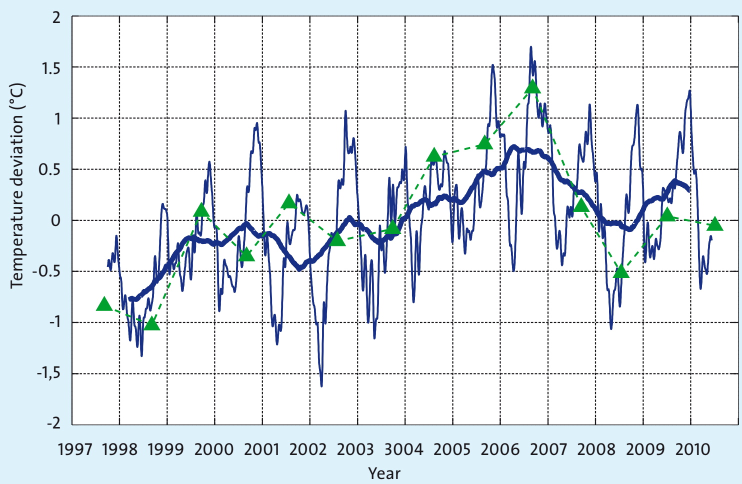
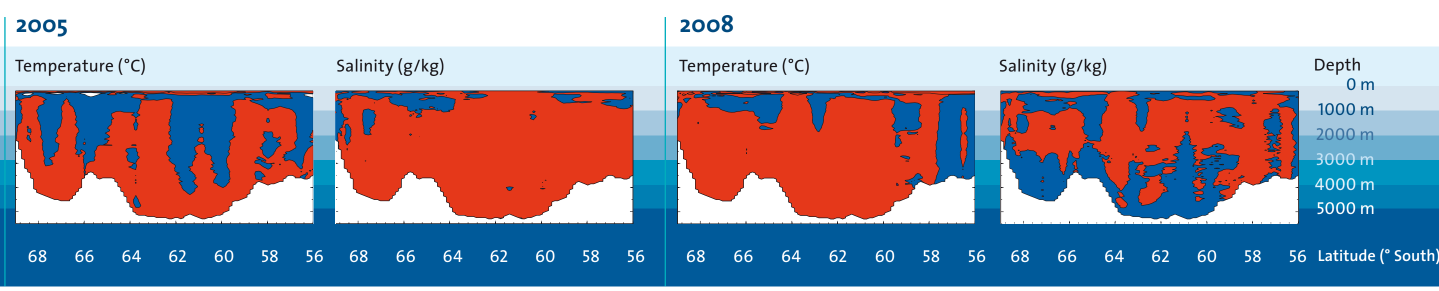


Fig 2: HAFOS consists of anchored devices, freely drifting floats and ice platforms that receive data from sensors under the sea ice. The data are transmitted to land stations via satellites.
Figure: Frauke Thiele-Wolff, AWI

Fig 3: Time series temperature

Time series of the temperature deviation of the Atlantic water (T>2 °C) relative to the long-term (1997-2009) mean value from the Fram Strait, measured in the West Spitsbergen Current. The continuous lines result from measurements with an anchored device, the dots were measured with a sensor from the ship in summer. The fluctuations over a period of several years, over which a possible trend is superimposed, are easily discernible.
Figure: Agnieszka Beszczynska-Möller, AWI





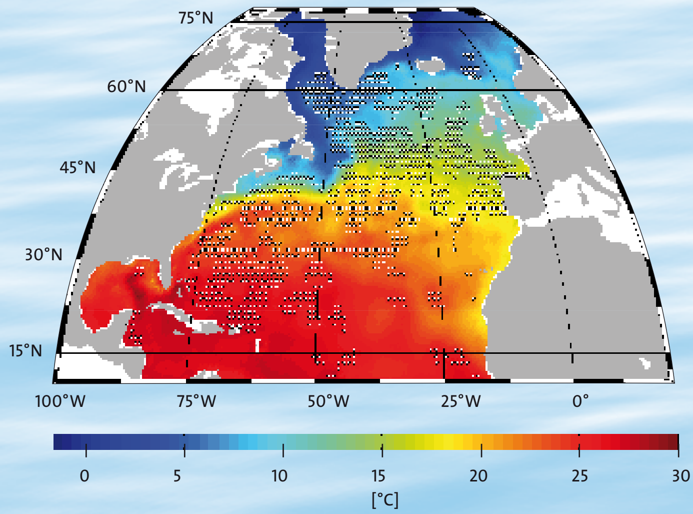
Sea level in the North Atlantic rose 6 cm in only 15 years

The climate in Europe is markedly influenced by the Gulf Stream and its continuation, the North Atlantic Current. For this reason changes in flow speed and heat transport are of great importance for Europeans. Using various measuring systems, the North Atlantic is continuously observed and changes are carefully monitored.

For many years the Alfred Wegener Institute has been using data from satellite measurements and drifting buoys in its analysis of currents, heat content, heat transport and the sea level.

Most data relate to the regular measurement of temperature and salinities and their stratification. They are derived from freely drifting buoys employed by the ARGO programme (Array for Realtime Geostrophic Oceanography). Although there are over 3,000 buoys worldwide, important areas of the ocean are consistently unobserved (Fig. 1). For this reason we supplement these direct measurements with remote sensing observations from satellites. By means of radar altimeters, the sea level is monitored on a large scale and the currents in the upper ocean are measured. We assimilate the different information concerning the North Atlantic in a computer model, as is typical for a weather forecast. It shows that the temperature and salinity in the entire North Atlantic fluctuate considerably. The results vary a great deal from place to place. Averaged for the entire North Atlantic, we observe a rise in the sea level of 6 cm in the last 15 years.

The gradual rising of sea level is not unique to the North Atlantic. Observations at different tide gauges indicate very different numbers from which a worldwide mean value is calculated. For this purpose we apply a method using neural networks, which allows us to correct for the influence of land mass movements on the observations. The results indicate that the sea level rose worldwide by an average of 1.7 millimetres per year in the last century (Fig. 2).



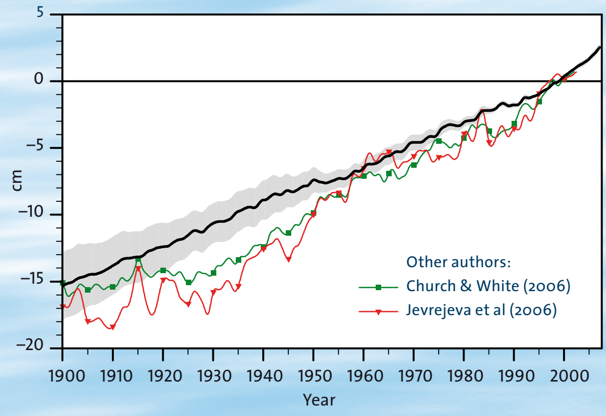


Fig 1: The surface temperature in the North Atlantic in 2005, as derived from direct and remote sensing measurements. The spatial distribution of the ARGO buoys for that year is shown by the small circles. Our analysis considers the temperature and salinity for all depths and years since 1998, and also includes the corresponding ocean current and heat transport.
Figure: Falk Richter, AWI

Fig 2: The rise in the global sea level in relation to the year 2000 (black line). The grey shaded area represents the uncertainty of the calculation. In comparison to the work of Church and White (green) and Jevrejeva et al. (red) we find fewer fluctuations between the years. All works are based on an analysis of water level gauges spread all over the world.
Figure: Manfred Wenzel, AWI

Our motivation for the development of a new ocean model

Since 1987 the Intergovernmental Panel on Climate Change (IPCC) has regularly issued reports on the present-day climate that summarise the state of the art. Furthermore, it presents climate forecasts up to the year 2100. However, none of their forecasts predicted the dramatic decline in sea ice at the North Pole. This and other weaknesses are largely based on an inadequate description of important processes. Small-scale events, such as the formation of deep water in the Weddell Sea and the Denmark Strait overflow, have major impacts on the global ocean. In order to better take these influences into account, we use an unstructured triangular grid with variable spatial resolution (Fig. 3). The model utilises modern computer architectures and can be carried out simultaneously on hundreds of processors. This allows for the computation of complex calculations within a reasonable time.

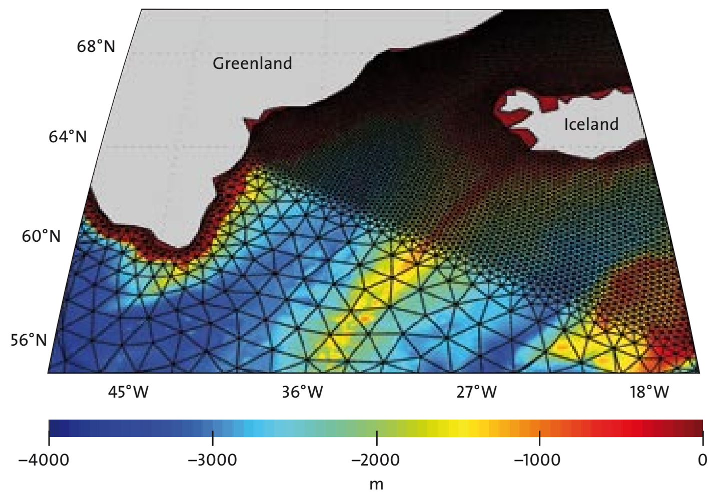


Fig 3: A detail of the bottom topography in a global ocean model. The spatial resolution of the model varies considerably and focuses on important regions like the Denmark Strait, located between Greenland and Iceland. Depicted is the triangular network structure that permits a smooth transition between fine and coarse resolutions in a seamless manner. The size of the triangles varies between 100 km on the open ocean and 10 km in the area of improved resolution.
Figure: Dmitry Sidorenko, AWI

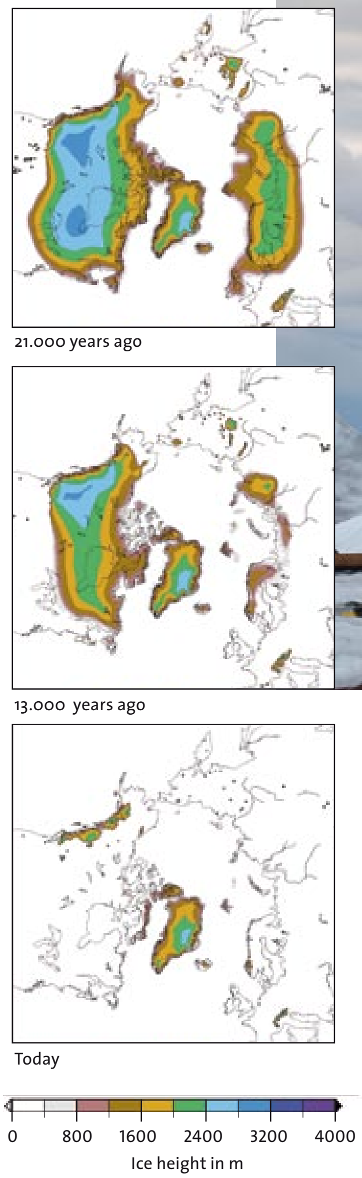


Fig 1: Modelling of icing in the northern hemisphere 21,000 years ago (top), 13,000 years ago (middle) and today (bottom) [ice height in m].
Data: Philippe Huybrechts, AWI
Figure: Johannes Freitag, AWI

Ice in climate change

The polar ice masses are the largest freshwater reservoirs on the Earth. They are a major component of the climate system and visibly react to climate fluctuations. If the dynamics of the ice sheet changes due to growth or loss of mass, this has repercussions for the climate system.

The changes in mass also influence the global sea level. This is why research on glaciological impact processes is extremely relevant for society. The polar ice masses, furthermore, are a unique archive for the composition of the atmosphere in the past.

Within the scope of glaciological research AWI concentrates on determining the mass balance and dynamics of the polar ice sheets to be able to model possible future changes. In addition, AWI scientists continuously work on improved interpretations of climate time series from polar ice cores by investigating the physical properties of the ice in detail.

Current glaciological work covers a broad range from satellite remote sensing, aircraft-aided radar measurements to determine the ice thickness and location of internal stratification all the way to microfocus X-ray tomography and electron backscatter on ice samples that are only a few millimetres in size.

As part of the satellite mission CryoSat-2, the researchers will observe over a period of several years the extent to which the surface height of the ice sheets changes. Complementary aircraft- and ground-based measurements serve to record smaller spatial scales as well and to gain a better understanding of the influence of the snow and

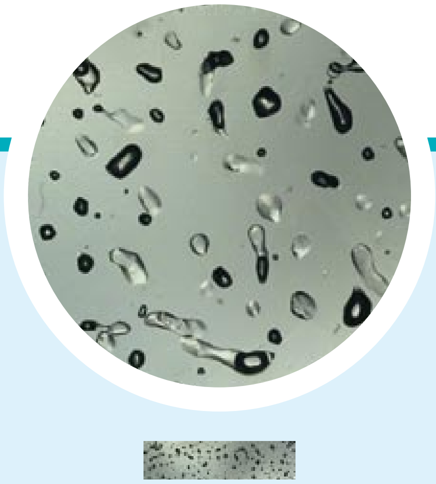


Fig 2: Air inclusions in a 2 cm wide and half a cm high Antarctic ice sample from a depth of 200 m.
Photo: Sepp Kipfstuhl, AWI

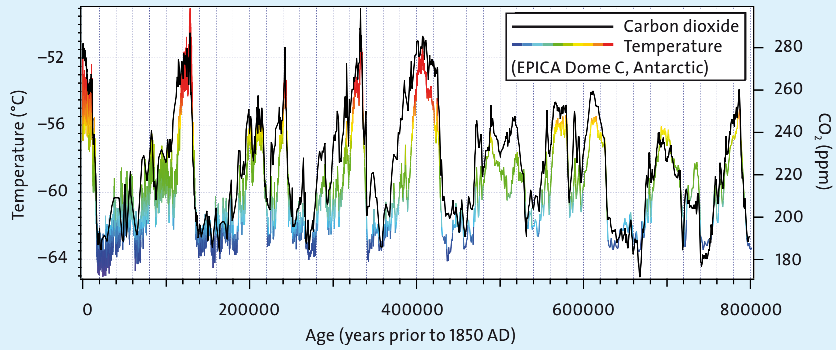


Fig 3: Temperature and CO_2 concentration

Time series of temperature and carbon dioxide concentration of the atmosphere over the last 800,000 years reconstructed from an ice core. The zero point corresponds to the year 1850. At present the CO_2 concentration is around 387 ppm. The CO_2 concentration can be regarded as a global value while the temperature only indicates the local conditions at the borehole site.
Data: EPICA, AWI
Figure: Johannes Freitag, AWI

firn surfaces on the backscattered radar signal. In connection with other satellite missions they can then draw conclusions regarding an increase or decrease in mass and focus their study on determining a causal relationship with observed climate changes. However, not only present-day data are used for this purpose. Complex computer models of ice dynamics try to replicate the currently observed ice sheet and glacier geometry and dynamics as realistically as possible (Fig. 1). If a model supplies a good result for the situation today, it can be used to investigate the changes in the ice masses in the past.

First of all the reconstruction of climate history on the basis of ice cores pursues the goal of looking as far back as possible in the past. Large-scale coupling to other climate archives, such as marine sediment cores as well as linking Greenland to Antarctic ice cores, play a special role in this context. In addition, an attempt is made to analyse and understand the variability of the climate, both temporally and spatially, on a continental to regional scale using several more recent ice cores. An aircraft-aided radar system that penetrates ice makes it possible to identify individual layers in a drilled core and pursue them further on an area-wide basis. In this way AWI scientists were able to link five deep Antarctic ice cores to each other in an aircraft campaign.

The air entrapped in ice plays a unique role in the analysis of ice cores (Fig. 2). Its composition in bubbles essentially corresponds to that of the atmosphere at the time of its entrapment. The temperature in the past can be reconstructed by analysing the isotope composition of the ice surrounding the air bubbles. This is the so-called isotope thermometer. The European project EPICA (European Project for Ice Coring in Antarctica) involved drilling into 800,000 years old ice, from which we find out something about the change in air composition and at the same time about temperature changes over this period (Fig. 3). By comparing the fluctuations in greenhouse gas concentration to the temperature fluctuations, we can learn a lot about the processes taking place in the climate system. Furthermore, inclusions in the ice core, e.g. dust or other aerosols, are important parameters for describing the palaeoclimate. An analysis of subglacial water may also provide important information on the time prior to icing, e.g. based on plant residues.

Both modelling ice dynamics and interpreting ice cores are based on a fundamental understanding of the processes and interactions occurring in an ice body. It is therefore necessary to examine a number of ice properties in basic studies. These include the processes that take place during the densification of snow and firn into ice. After all, a change in firn structure influences the inclusion of the climate signal in the ice as well as – on a microscale – ice deformation.

Ice wedges grow by virtue of frost cracks in the ground. If this process repeats itself every year, the ice wedges criss-cross the permafrost soil like a grid.

Global warming threatens permafrost regions and thus the global climate system

Permafrost forms in areas with a very low annual mean temperature and is defined as soil, sediment or rock (including ice) that remains below 0 °C for at least two consecutive years. Permafrost is a widespread phenomenon in the Arctic and in the non-glaciated areas of the Antarctic.

In the northern hemisphere 22.8 million km^2 and thus 24 % of the mainland are underlain by permafrost (Fig. 1). The thickness of the permafrost varies from less than a metre to several hundred metres and can even reach more than 1,500 metres in central Siberia. In many regions of the Arctic, permafrost can also be found under the present-day shelf seas. During periods with lower sea level, i.e. during the glacial periods of the ice ages, extensive shelf areas of the Arctic stayed dry and permafrost formed that continues to exist today as submarine permafrost – after the flooding of these regions. Ice is often present in permafrost and is termed 'ground ice'. It is formed during the freezing of the ground and may grow as an ice wedge or as a massive body of ice.

Permafrost and global climate change

Changes in the permafrost observed in many places in the Arctic since the late 1960s have occurred due to warming and involve severe degradation of permafrost. New permafrost, on the other hand, forms only to a minimal extent. An initial warming of the permafrost surface causes the bottom of the active layer (which is created by the thawing of the surface of permafrost areas during the summer months) to move further downward. If warming persists, this active layer reaches down to deeper permafrost layers.

A consequence of thawing permafrost is the emission of gases stemming from microbiological processes, i.e. primarily carbon dioxide and methane. As the active layer deepens, carbon present in the now thawed permafrost is made available to microbes that transform it into carbon dioxide and methane. According to the most recent estimates, around half of the organic carbon stored in the ground worldwide is stored in permafrost and Arctic permafrost contains twice as much carbon as the entire atmosphere.

Permafrost thawing has other consequences on the ecosystem. The erosion of the Arctic permafrost coast (which makes up 34 % of the global coastline) leads, for instance, to increased deposition of sediment, carbon and pollutants in the Arctic coastal seas. If the thaw layer extends deeper into the ground or permafrost disappears, the result is damage or even destruction of buildings (Fig. 3). The current warming consequently poses a threat to the entire infrastructure built on permafrost.

Fig 1: Permafrost distribution in the northern hemisphere and main areas of AWI research
Map: Hugues Lantuit, AWI; Source: International Permafrost Association

Fig 2: Abandoned buildings in the port of Tiksi (northern Siberia) that were deformed by thawing permafrost.
Photo: Hugues Lantuit, AWI

AWI permafrost research projects

The Alfred Wegener Institute covers a broad spectrum of permafrost research and is the largest institution for permafrost research in Europe outside Russia. Prof. Dr. Hans-Wolfgang Hubberten, head of the AWI Research Unit, has been president of the International Permafrost Association (IPA) since 2008. This marked the first time that an IPA president was designated from a country not bordering the Arctic.

AWI is involved in many facets of permafrost research, including geology, geomorphology, hydrology, geochemistry, microbiology, limnology (study of lakes and other freshwater systems), carbon cycles, energy balance, modelling, remote sensing, geophysics and palaeogeography. It provides a unique and multidisciplinary environment for permafrost science. These research topics are extensively integrated into international observing programmes and international partnerships.

Jointly with Russian colleagues, AWI has carried out several drillings in the Siberian permafrost and measured permafrost temperature using thermistor chains. These boreholes continuously supply temperature data that are fed into the Global Terrestrial Network for Permafrost (GTN-P) of the Global Terrestrial Observing System (GTOS) and the Global Climate Observing System (GCOS).

AWI scientists are primarily active in carbon cycle research. They study the transformation of carbon into greenhouse gases by microorganisms in the permafrost regions of Siberia, Alaska, Spitsbergen and Canada (Fig. 1). Based on investigations of the emissions of greenhouse gases, material and energy flows in permafrost over several years, they determined that greenhouse gases are in fact released from the upper layer of permafrost during the summer.

Another focal point of AWI's activities involves the study of changes in Arctic coasts and submarine permafrost. The results obtained make it possible to estimate the deposition of sediment, carbon and pollutants in the Arctic coastal seas and the ocean. For over ten years now AWI has headed the international project Arctic Coastal Dynamics, which makes a significant contribution to characterisation of the processes that take place in the coastal areas of the Arctic Ocean as well as to quantification of coastal erosion.

AWI is also recognised worldwide in the field of palaeo-environment reconstruction in permafrost. This provides a picture of permafrost dynamics during climate fluctuations in the past, thus leading to a better understanding of the present and future distribution of permafrost. By virtue of their years of experience in the entire Arctic, AWI researchers have created a unique permafrost archive spanning the whole circum-Arctic.

Marine climate archives – learning from the past to get a sharper picture of the future

There is general agreement that current and future climate development is subject to significant change due to the anthropogenic greenhouse effect. The extent of this change is controversial, however. An improved assessment requires precise knowledge of the natural climate fluctuations, i.e. from periods in which human influence did not yet play a role or at most a minor role.

First and foremost, climate research needs information on the duration, speed, frequency and regional patterns of long-term and short-term climate fluctuations and on how anthropogenic impacts and natural climate fluctuations mutually influence each other. A special challenge in this context involves so-called tipping points in the climate system. Even minor uniform fluctuations in the climate system may lead to drastic, irreversible and abrupt climate changes that would pose a challenge with respect to the adaptation options of human society.

Unfortunately, instrumental climatological measurement series go back only a maximum of several centuries and only at a few places on Earth. To gain a comprehensive understanding of the global climate system and its future development, a considerably more extensive time perspective is necessary. That is why marine geology researchers at AWI focus on palaeo-environment reconstructions on a wide variety of time scales, primarily in polar regions that react particularly sensitive to slight global climate fluctuations. Drill cores from the Antarctic region and Arctic basins supply information on changes and stability of the ice sheet. A major research topic here is the study of geological periods that were characterised by a similar or even warmer climate than today.

A prominent example is the Pliocene age, 3 to 5 million years ago (Fig. 1). At that time, the global mean temperatures were about 2-3 °C higher and roughly corresponded to the temperature rise expected towards the end of the 21st century. In the international ANDRILL (Antarctic Geological Drilling) research project, AWI scientists are reconstructing Pliocene evolution of

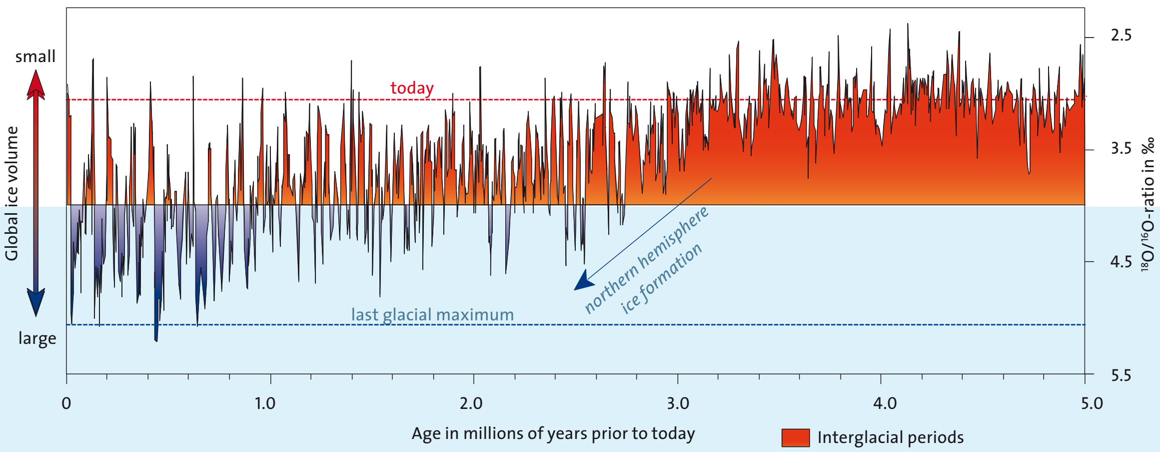


Fig 1: Fever curve of Earth's climate

Climate development over last 5 million years. The oxygen isotopes were measured along a sediment core of fossil calcareous shells of benthic foraminifera (unicellular organisms living on the seafloor) – they are an indicator for fluctuations in the global ice volume.
Figure: Ralf Tiedemann, AWI

the West Antarctic ice sheet in order to assess its sensitivity to global temperature increases (Fig. 2). The results point to a repeated melting of the West Antarctic during the Pliocene. A complete loss of the present West Antarctic ice cap would increase the global sea level by 2-3 m. Whether and when such a scenario might occur in connection with the current climate warming is the subject of present-day research.

In addition to the ice caps, the sea ice cover plays a special role in the global climate system since sea ice reflects sunlight to a much more pronounced extent than the surface of the water. Consequently, changes in the distribution of sea ice may reinforce a warming or cooling trend. At present, particularly the drastic summer decline in sea ice in the Arctic has become a focal point of research. On the other hand, little is known about the historical development of the sea ice cover further back than the last 150 years. This is primarily due to the fact that there are no reliable reconstructions for the Arctic based on sediment core data.

For the first time, a new method that has been further developed at AWI now promises more precise insights into the dynamics of sea ice distribution (Fig. 3). With the help of fossil organic molecular residues produced by algae living in the sea ice, AWI researchers have succeeded for the first time in reconstructing the sea ice cover of the last 30,000 years for part of the Arctic based on sediment cores. The latter indicate that the seasonal spread of sea ice was subject to drastic and short-term changes. More extensive studies are aimed at recording the regional patterns of sea ice distribution and helping to assess future development better.

Marine geologists at AWI organise research expeditions to the Arctic and Southern Oceans involving a considerable logistics effort. Currently, our expeditions concentrate on obtaining marine sediment cores from the North and South Pacific to erase the last large white spots on the world map of palaeo-climatology. This will complete the network of sediment cores spanning the poles for the first time. These sediments are aimed at extending our understanding of temporal changes in oceanic circulation, sea ice distribution and thus related fluctuations in biological productivity as well as in ocean-atmosphere exchange processes of carbon dioxide. In some cases, these sediments even permit reconstructions on time scales ranging from seasons to decades. A special focal point of our studies are the interglacial maxima of the last 500,000 years, in which the global temperature and the sea level were in part slightly higher than today.

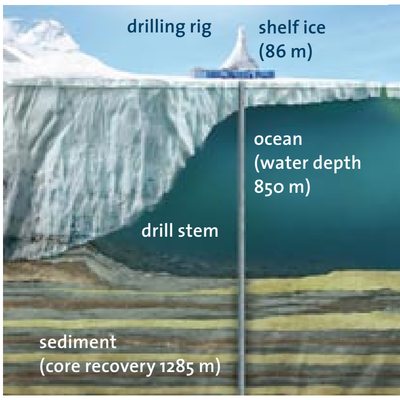
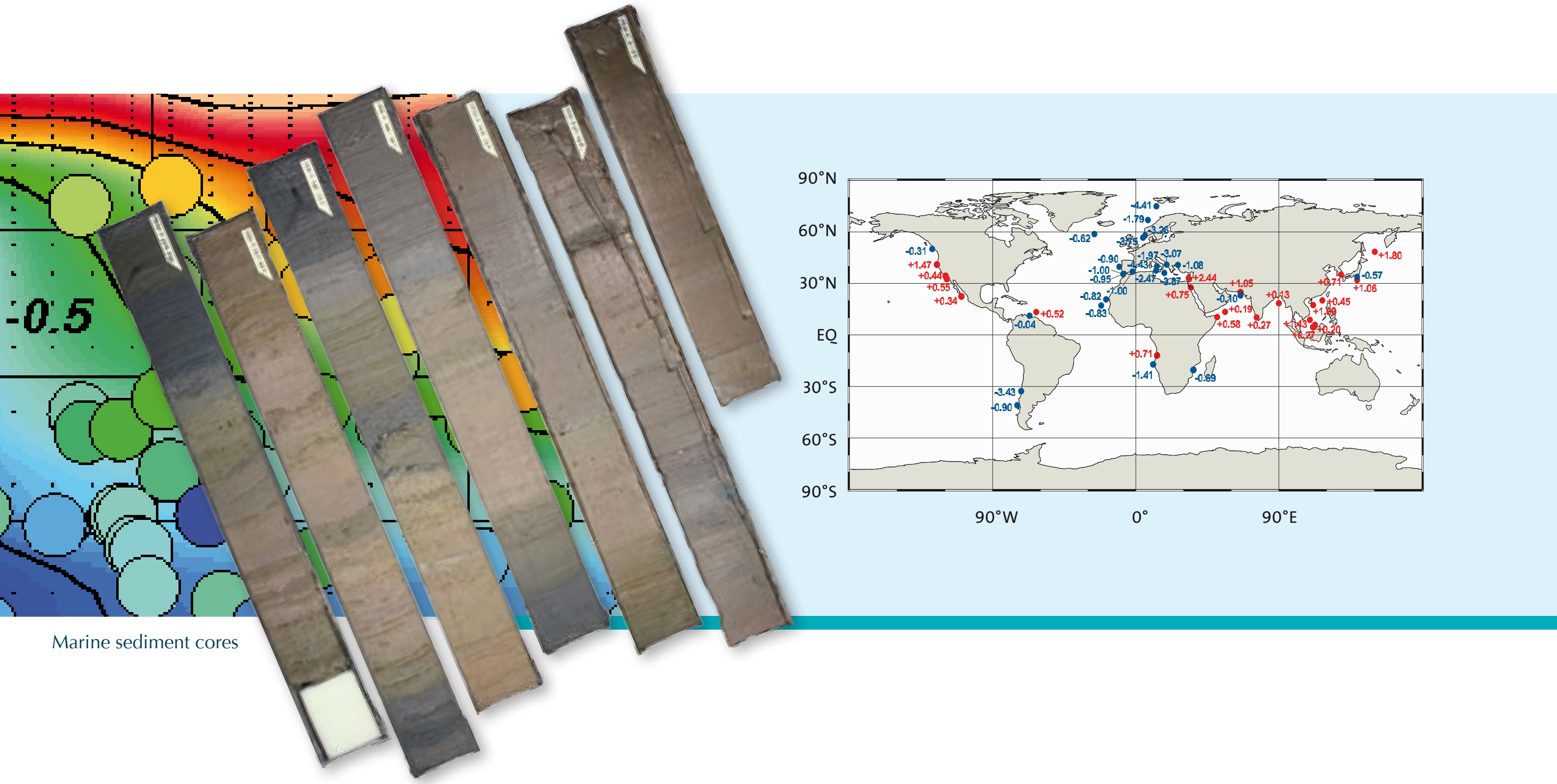


Fig 2: Marine sediment successions were obtained from a drilling rig anchored on the Antarctic Ross Ice Shelf within the framework of the ANDRILL programme.
Figure: Angie Fox, ANDRILL SMO

Fig 3: Sampling sea ice from on board the 'Polarstern'. The light-brown colour of the ice results from ice algae growth.
Photo: Juliane Müller, AWI



Marine sediment cores

Palaeoclimate models: back to the future

Climate development over the past ten to one hundred thousand years has decisively contributed to the development of our present-day society and culture. Nevertheless, surprisingly enough, little is known about climate development during this period.

This applies in particular to the interplay of external drive mechanisms (change in insolation, expansion of the ice sheets, varying greenhouse gas concentrations) with internal feedback processes in the climate system. It has become evident that a better understanding of these interactions can only be achieved by linking measurement data from climate archives (e.g. ice cores or marine sediments) to new theoretical concepts and climate simulations. Particularly simulations with complex climate models enable clear allocation of observed climate changes to external driving factors and internal feedback processes. Such an analysis is not possible by means of an evaluation of climate archives alone.

Fig. 1 compares reconstructed and modelled temperature changes of the last 7,000 years. Reconstructions of sea surface temperatures based on measurements are statistically analysed for these studies (Fig. 1a). The resulting pattern shows cooling at high latitudes (blue) and warming at low latitudes (red). Simulation calculations with a complex climate model display a pattern in temperature trends that is consistent with the reconstructions (Fig. 1b). Furthermore, it turns out that the long-term climate variability can, for the most part, be explained via a simple model concept that only takes into account the direct local reactions to higher or lower external insolation (Fig. 1c).

Current models of the Earth system not only map its physical aspects, but also integrate the biosphere and biogeochemical material cycles. Since recently there have even been attempts to simulate variations that can be measured in the climate archives directly and then compare them to the real data. An example of this is the simulation of concentrations of three different carbon isotopes (^{12}C, ^{13}C, ^{14}C) in the atmosphere and ocean. The ratio of the stable isotope ^{13}C to 'normal' carbon ^{12}C permits us to draw conclusions about the past distribution of water volumes and biological productivity in the ocean. Fig. 2a shows the simulated ^{13}C / ^{12}C distribution

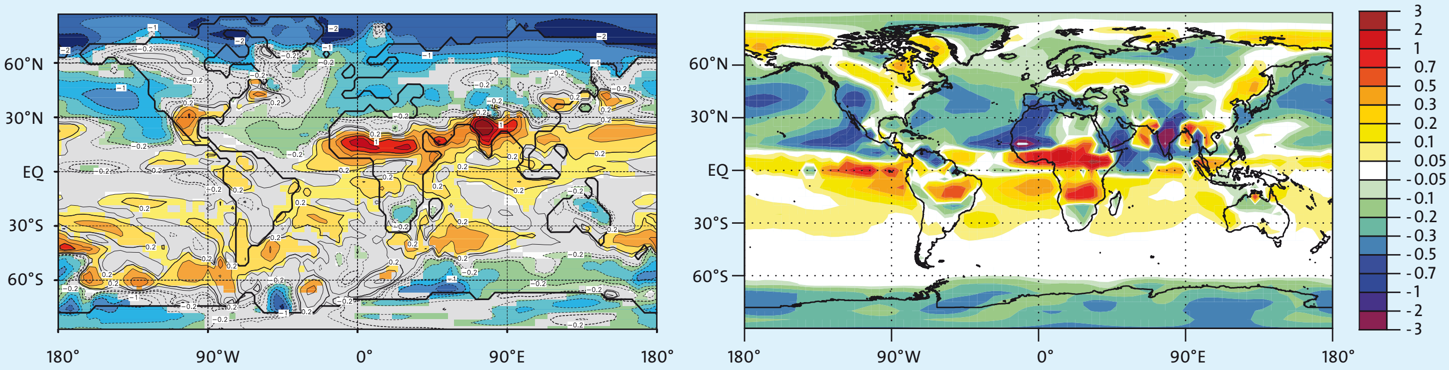


Fig 1a-c: Temperature trends for the last 7,000 years in °C

a left) Reconstructions based on alkenone data (Rimbu et al., 2003),
b middle) Simulations with a complex climate model (Lorenz and Lohmann 2004),
c right) Derived temperature trends from a theoretical, statistical model concept (Laepple and Lohmann, 2009)

for the last ice age. For the North Atlantic the modelled distribution matches well with the reconstructions for the situation 20,000 years ago based on marine sediment cores. In the South Atlantic, by contrast, significant deviations are evident in the simulation, pointing to a deficit in the model with respect to this region.

The ratio of the instable radioactive isotope ^{14}C to the normal ^{12}C makes it possible, among other things, to determine the age of marine sediments. Because of natural imbalances in the carbon cycle, however, the ^{14}C age of a marine sample is always greater than the ^{14}C age of an atmospheric sample from the same period. This difference in age is called reservoir age and gives rise to systematic errors in determining the age of marine samples. Simulations of the past $^{14}C/^{12}C$ ratio on the ocean surface provide important information for the necessary corrections of such errors. Fig. 2b, for instance, shows that at the high point of the last ice age the marine reservoir age, particularly at high latitudes, was several hundred years higher than today and in a ^{14}C age determination of a marine sample the calculated age of the samples has to be corrected by this figure.

Such new model concepts and complex climate simulations, which also take into account biogeochemical material cycles, thus result in entirely new ways of gaining a better understanding of the Earth's history. Especially with an eye to the already occurring as well as future climate change, modern palaeoclimate research has therefore become a focal point of interest.

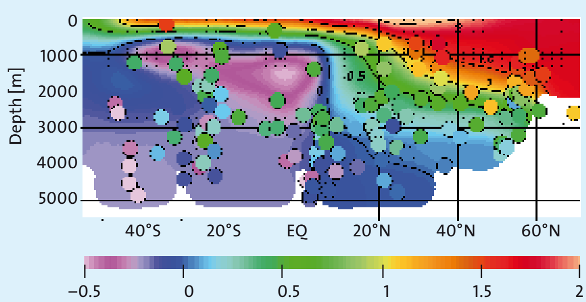


Fig 2a: Meridional distribution of ^{13}C concentration in per mille based on the standard value PDB in the glacial Atlantic 20,000 years ago: model (contours) and reconstructions (circles).
(Hesse et al., submitted)

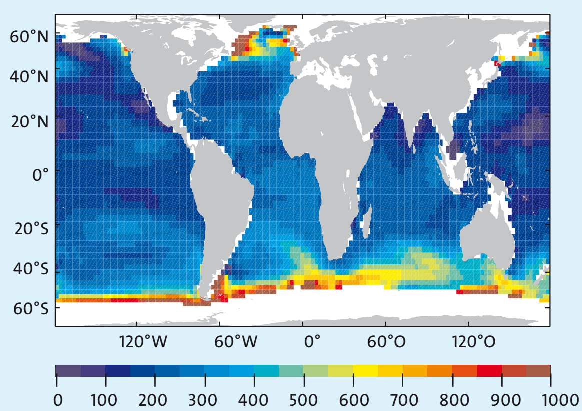
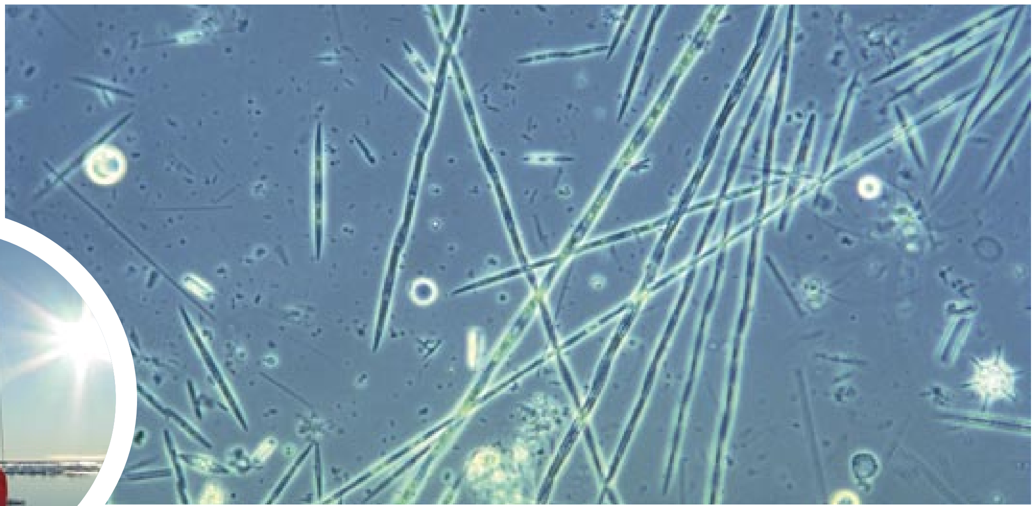


Fig 2b: Modelled changes in ^{14}C age of surface water (in years) between the last ice age 20,000 years ago and today.
(Butzin et al., 2008)



Marine plankton influences global climate

The currently rising water temperatures in the polar regions are causing the sea ice cover to shrink. Simultaneously, the globally increasing concentrations of the atmospheric gas carbon dioxide (CO_2) are acidifying seawater. These environmental changes have an impact on the biology of the polar seas that, in turn, interacts with processes that are integral to the entire Earth system.

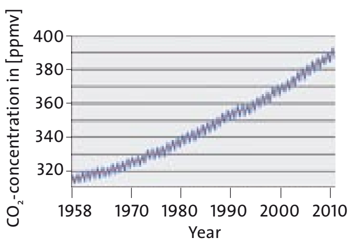


Fig 1: Atmospheric CO_2 concentration at Mauna Loa, Hawaii, from 1958 to September 2010 (blue curve) and trend (red curve). Besides the rise in CO_2 concentration, the graph indicates the seasonal variation caused by the vegetation periods in the northern hemisphere. Within only 50 years the CO_2 concentration in the atmosphere has risen more than a fourth.
Data: www.esrl.noaa.gov/gmd/ccgg/trends;
Figure: Renate Treffeisen, AWI

Growth of microscopic algal and animal species (plankton) influences carbon transport, and thereby the global climate as a whole. These individual processes are controlled by nutrient levels and/or trace substances.

Brief history of life, ice and oxygen

Life on the young Earth unfolded in an oxygen-free atmosphere. The first forms of life developed enzymes containing iron to regulate their metabolism. The oxygen production of the plants transformed the anoxic atmosphere into an oxygen-enriched, oxidising atmosphere. Iron rusts to form iron^{3+} salts that are considerably less water-soluble than iron^{2+} salts and sink. As a result, the ocean undergoes iron depletion, which inhibits algal bloom in regions remote from land. In interglacial periods ocean deserts low in iron and growth continued to expand. During the ice ages, by contrast, the land surface dried up and iron dust, which was increasingly blown onto the sea, caused the phytoplankton to turn green.

Interactions between ocean and atmosphere

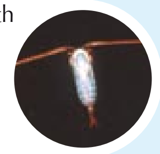
The concentrations of CO_2 in the atmosphere and ocean balance out by virtue of molecular diffusion and solubility. When warm surface water from the subtropics is transported to polar regions with the North Atlantic Current (Gulf Stream) and cools down there, it takes up additional CO_2. As soon as CO_2 dissolves in water, a cascade of chemical equilibrium reactions involving, among other things, carbonic acid commences. As a consequence, the ocean contains 50 times more carbon than the atmosphere. The concentration of CO_2 in the atmosphere has been increasing drastically for approx. 200 years (Fig. 1). The world ocean has taken up around 30 % of this new, 'anthropogenic CO_2'. Without the ocean the concentration in the atmosphere would be correspondingly higher. The more CO_2 dissolves in the ocean, the greater the pH value drops.

Oceanic carbon pumps

Carbon is transported from the ocean surface to the deep sea via three major 'oceanic carbon pumps' (Fig. 2).

- The solubility pump transports dissolved inorganic carbon (CO_2 and its ions). CO_2-enriched surface water sinks in the polar regions and flows from there to all deep-sea areas of the Earth. Since it does not appear in the subtropics again until after more than 500 years, the transported carbon goes into 'intermediate storage' for the time being.
- Organic carbon is carried away by the 'biological pump'. It forms from CO_2 when microscopically small phytoplankton algae build up their biomass through photosynthesis with the help of sunlight. The animals of the zooplankton, which are almost just as tiny, consume phytoplankton and exhale CO_2. Bacteria additionally give off dissolved organic carbon as a sticky slime. Plankton cells also secrete a transparent, carbon-enriched substance that sticks together small plankton particles to form larger units. Such marine snow is large and heavy enough to sink down to a water depth below 500 m. About 10 %

of the particulate organic carbon of the surface water layer sinks to greater sea depths. Only 1 % of the annual production is carried from the upper ocean layers to the deep sea floor with the ‘biological pump‘, the rest is consumed in the deep ocean. The deep-sea fauna, in turn, uses up to 90 % of this so that only 0.01 % of the original production is stored in sediments.



- The carbonate counterpump releases CO_2 when calcareous marine organisms like calcareous algae grow. When they reproduce, for instance, at the expense of diatoms, as in the Arctic Ocean in recent years, deep-sea carbon transport is significantly reduced. Our research programmes are aimed at quantifying these effects.

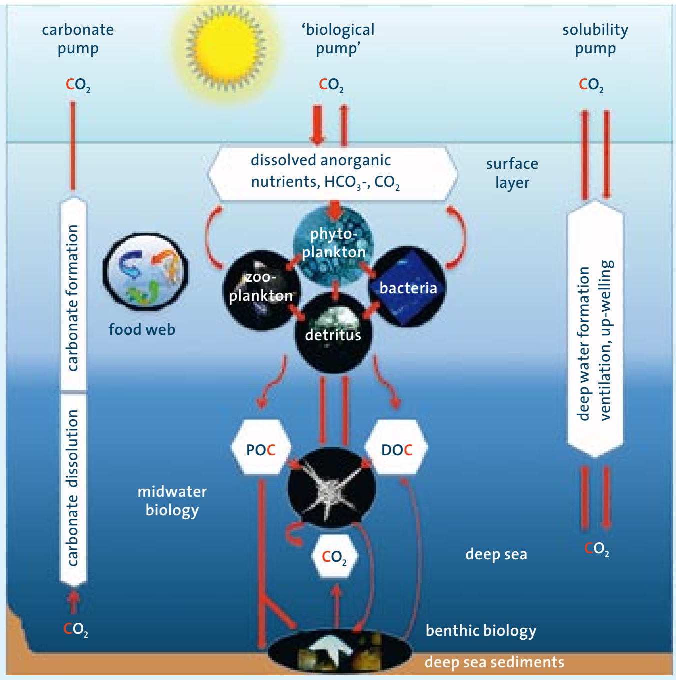
Regulation of the ‘biological carbon pump’

At AWI we examine the effectiveness of the ‘biological carbon pump‘ by means of experiments in the polar oceans during the expeditions with the research vessel ‘Polarstern’. In this context we have verified in observations in the ocean and through experiments on board the research vessel that through respiration zooplankton converts considerable organic carbon into CO_2 near the ocean surface while grazing the phytoplankton. Given a good light supply, phytoplankton production is high if sufficient nutrient salts are available. In extensive sections of the Southern Ocean the total amount of dissolved nutrient salts is not consumed by virtue of primary production in the course of the year. However, the algae often suffer from iron shortage. Can the productivity and thus the absorptive capacity of the ocean for carbon be increased through artificial iron fertilisation? Since the plants lack iron for growth, a slight addition of iron^{2+} should lead to an increase in algae production and to stimulation of the ‘biological carbon pump’ in otherwise optimal areas (Fig. 3).

Iron fertilisation as a CO_2 sink?

Uncertainty prevails concerning the controversial approach of removing CO_2 from the climate cycle of the Earth by means of sustained iron fertilisation. Unexpected algae species could profit from this, with unknown effects in the food web. Some phytoplankters produce gases like DMS that are extremely relevant for the climate. An intensive ‘biological pump’ could lead to increased degradation of biomass and augmented oxygen consumption. There is a lack of information on reactions of marine fish or mammals to iron fertilisation. Formation of harmful algae or those producing climate gases has not been observed to date, either in connection with natural or stimulated iron fertilisation. The same applies to layers with weak or deficient oxygen concentration in such areas, though a weak oxygen concentration is typical for upwelling areas with intensive algae production.

Besides harmful side effects in the ecosystem, there is a risk that CO_2 dumping in the ocean would hinder necessary strategies for avoiding CO_2 release. On the other hand, the increase in marine productivity due to iron fertilisation could provide zooplankton and thus whales a better food base. Scientific experiments are the only way of finding answers to such questions. The climate models developed at AWI take into account both the physical / chemical processes and the most important biological reactions.



Bathmann & Passow (2010) Biol unserer Zeit 40: 304-313 DOI: 10.1002/biuz.201010429: Copyright Wiley-VCH Verlag GmbH & Co. KGaA.

Fig 2: The three oceanic carbon pumps
Dissolved CO_2 is transported through the upwelling and downwelling of the water caused by the solubility pump (right). The ‘biological pump’ is based on the uptake of carbon by organisms and their sinking to the seafloor (centre). When calcification takes place, CO_2 is released and one therefore refers to a carbonate counterpump (left). The algae and animals of the plankton in the upper part of the ‘biological pump’ turn over a substantially greater amount of carbon than the dissolved (DOC) or particulate (POC) organic carbon that sinks to deeper water layers. In the deep ocean the sinking material is biodegraded further and released in this process as CO_2.

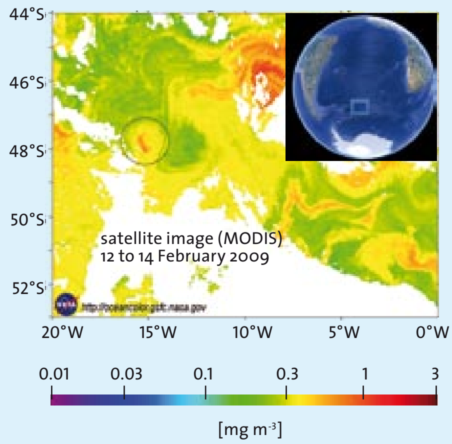


Fig 3: The plankton bloom (red section in the circle) generated by the German-Indian project LOHAFEX in the South Atlantic, as seen from the MODIS satellite. The colour coding reflects the algae concentration in the ocean. The other red, yellow and green areas indicate regions of natural algae concentrations measured as chlorophyll. White sections are cloud areas through which the satellite cannot see the water. The rectangle in the small picture at the top right shows the geographic location of the LOHAFEX area in the South Atlantic.
Figure: modified according to Christine Klaas, AWI

REKLIM investigates regional climate change with the help of observations and models.
(Source: Helmholtz Network Regional Climate Change, REKLIM, 2010)

Regional impacts of climate change become focus of attention

Interactions between atmosphere, ice, ocean and land surfaces have always influenced the climate on the Earth. In order to better describe the related exchange processes and long-term developments in the climate system, global climate models have successfully contributed to gaining an initial understanding of large-scale natural climate fluctuations in the past years.

However, many processes that influence the climate on different temporal and spatial scales have yet to be investigated extensively.

At present there is broad agreement in the scientific community that, with a high degree of probability, the current warming of the Earth (Fig. 1) is primarily attributable to increased concentrations of greenhouse gases and altered land use. However, the specific impacts on individual regions have not been well understood thus far. There is not sufficient scientific evidence, for example, to determine whether climate change is the cause of drier summers or wetter winters in a certain region. For agricultural use, however, this is the decisive question. By the same token detailed scenarios regarding the rise in global sea level, for instance, are important for political and economic decision-making processes in order to be able to adapt coastal protection measures accordingly.

To explore this and other topics and be in a position to make more precise statements, eight research centres of the Helmholtz Association have joined to form the Helmholtz Network Regional Climate Change (REKLIM): the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven, the German Aerospace Centre (DLR) in Oberpfaffenhofen, the Jülich Research Centre, the German Research Centre for Geosciences in Potsdam (GFZ), the GKSS Research Centre in Geesthacht, the German Research Centre for Environmental Health in Munich, the Karlsruhe Institute of Technology (KIT) as well as the Helmholtz Centre for Environmental Research (UFZ) in Leipzig (Fig. 2).

The spectrum of research topics ranges from regional climate modelling of the Earth system, observation programmes in the Arctic and in Europe as well as investigation of the contribution of chemical processes in the atmosphere all the way to analysis of extreme weather events, such as hail, storms, floods and drought. They include questions concerning socio-economic consequences, management of climate influences and development of adaptation strategies.

In this connection the research network attempts, among other things, to find answers to the following questions: How does the deve-

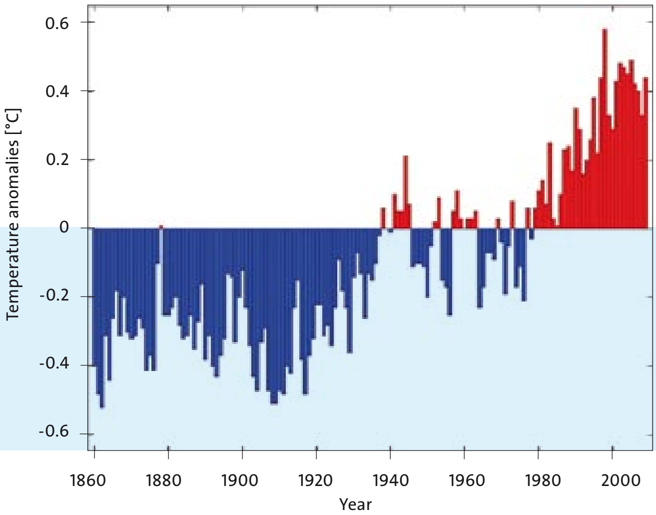


Fig 1: Global anomalies of air temperature on the Earth's surface in the period from 1860 to the present. (Data: IPCC, 2007, updated)

lopment of our climate depend on the interaction between atmosphere, ice, ocean and land surfaces and how do anthropogenic impacts and natural climate fluctuations influence each other? How great are the losses of continental ice masses (particularly of Greenland) and how does the sea level react to melt water run-off and warming? What causes the substantial changes in sea ice and permafrost in the Arctic and what are the related local and remote impacts? What consequences from climate change do ecosystems, water resources as well as agriculture and forestry in Germany and the Alpine region have to reckon with? How is the regional climate influenced by changes in the components of the air? How will extreme events like storms, floods and drought change with climate change? And finally: How can we choose the optimal strategy for adaptation and mitigation?

To answer these questions, the scientists at the eight centres use data from remote sensing satellites, floating and airborne research platforms, such as the research vessel 'Polarstern' and the research aircraft 'Polar 5' and 'Halo', as well as stationary observation stations like the environmental observatories TERENO and the atmosphere simulation chamber SAPHIR. The databases for model calculations are improved by means of the extensive measurement data because this is the only way to develop high-resolution analyses and scenarios. The interaction of observations and process models and the interdisciplinary networking of the scientists in the research network will thus contribute to optimising the coupled climate models used. This makes it possible to derive detailed statements on the reaction of the climate system to the changing climate boundary conditions on a regional to local scale. The specific results are especially important and necessary so as to be able to better inform decision-makers in the political arena, in industry and at government agencies as well as the general public about risk potential in regional development and to contribute to the development of sustainable adaptation and mitigation strategies.

Fig 2: REKLIM

The eight research centres of the Helmholtz Network Regional Climate Change (REKLIM). (Source: Helmholtz Association)

The BSRN radiation measurement fields at two of AWI's polar research stations: Neumayer in Antarctica and Ny-Ålesund in the Arctic.

The World Radiation Monitoring Center at AWI: a central worldwide data archive for Earth system sciences

The word 'climate' comes from Greek and means 'inclination'. As a matter of fact, the mean inclination of the Sun to the Earth's surface has decisive impacts on our climate zones. Of course, there are diverse other factors that influence the radiation balance and thus the climate of our Earth: such as the anthropogenic rise in the greenhouse gas CO_2 and the diminishing reflectivity of the Earth's surface due to melting snow and ice.

Long-term radiation measurements are of great importance for climate researchers. When the Intergovernmental Panel on Climate Change first turned its attention to the compilation of climate research knowledge in the 1980s, it perceived that the quality of the existing radiation measurements often did not meet the standards of modern climate research. This situation thus led to the establishment of the Baseline Surface Radiation Network (BSRN) within the framework of the World Climate Research Programme in 1992. The objective of this global network is to carry out the best possible surface radiation measurements at a few selective stations around the globe. The core of the network is its central archive, which all climate researchers can freely access. AWI has been operating this World Radiation Monitoring Centre (WRMC) since 2008.

How did this come about? Bipolar research is part of the core business of the Alfred Wegener Institute for Polar and Marine Research (AWI). AWI has maintained two permanently manned polar research stations in this connection: the Neumayer Antarctic research station in Queen Maud Land since 1981 as well as the Koldewey Arctic research station in Ny-Ålesund on Spitsbergen since 1991. The continuous measuring programmes of the two stations have included extensive surface radiation measurements right from the beginning. Together with seven other stations, the two AWI stations formed the nucleus of the BSRN in 1992.

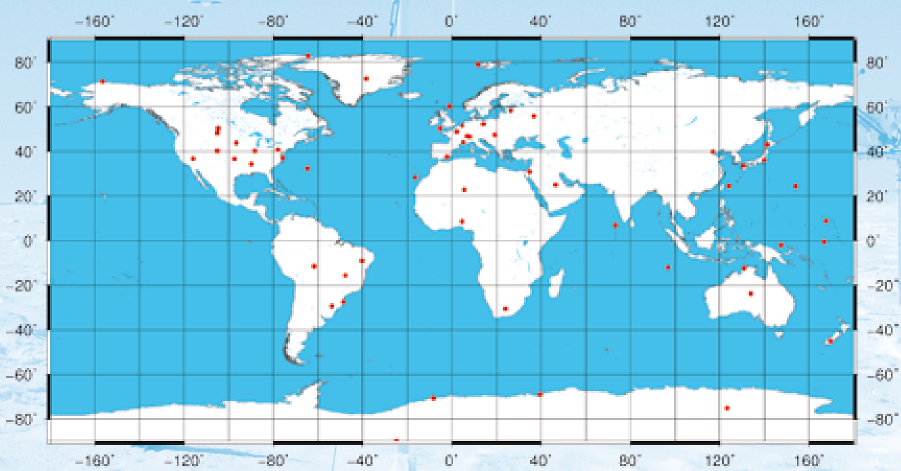


Fig 1: The world-wide network of measurement stations
Figure: Wolfgang Cohrs, AWI

Fig 2: Glass domes of a pyranometer during the polar night at Neumayer. The pyranometer serves to measure solar and diffuse sky radiation.
Photo: Gert König-Langlo, AWI

The World Radiation Monitoring Center was developed at the same time under the direction of Prof. Ohmura at the Swiss Federal Institute of Technology Zurich (ETH). When Prof. Ohmura retired, the search commenced for a new operator. Because of its scientific expertise and outstanding IT infrastructure, the Alfred Wegener Institute was chosen.

The World Radiation Monitoring Center was given a new face at AWI. In addition to the file archive it took over, all data were imported into the PANGAEA information system. This archive serves the purpose of archiving, publishing and distributing geo-referenced data in the field of Earth system research (http://www.pangaea.de). The WRMC website was also completely redesigned (http://www.bsrn.awi.de/). Besides the stations' large volume of metadata, the WRMC homepage now offers clearly structured link lists for direct access to all data via PANGAEA. In the meantime 5,800 station-months of data are available from 51 stations.

The World Radiation Monitoring Center not only stores the radiation measurements of many stations which have been sampled every minute, but also many complementary meteorological observations that are necessary to interpret radiation measurements. They include the vertical profiles of air temperature and humidity obtained by means of weather balloons as well as cloud observations and cloud heights.

Globally, the surface radiation is estimated via satellites. Comparison with the direct measurements of the WRMC makes it possible to improve their accuracy. Climate models, too, rely on methods for supplying data on surface radiation. These radiation calculations can be checked and optimised with the data from the World Radiation Monitoring Center. Trend analyses are also possible using the WRMC measurements since some stations have been operating continuously for 18 years already. Initial results indicate trends in the radiation coming from the Sun, very probably as a consequence of changes in the air pollution control policy. Insolation rises over regions with decreasing air pollution whereas it drops over India and China.

Fig 1: The Climate Office for Polar Regions and Sea Level Rise is active in the network of regional climate offices of the Helmholtz Association.
(Figure adapted from: Schipper, J.W., I. Meinke, S. Zacharias, R. Treffeisen, Ch. Kottmeier, H. von Storch und P. Lemke, 2009, DMG Nachrichten 1-2009)

Climate consulting: regionally specific, comprehensible, solid – the Helmholtz Climate Office at AWI

Global climate change varies greatly in its regional impact. Adaptation strategies in response to climate change have to take these differences into account in order to avoid misinvestments, among other things. Because of the constantly growing need for consulting services, the Helmholtz Association has set up a network of four regional climate offices, one of which is based at the Alfred Wegener Institute as a Climate Office for Polar Regions and Sea Level Rise.

The regional Helmholtz climate offices (Fig. 1) are not only networked to each other in connection with their specific field, but are also integrated into the Helmholtz Association's user-oriented climate research, which includes climate protection as well as climate impact and adaptation research. Furthermore, they cooperate with excellence initiatives, universities, state and federal authorities. Their comprehensibly presented research results on specific regions and natural spaces are available to the actors and decision-makers involved in politics, industry and society as well as the entire public. The objective of the four regional Helmholtz climate offices is to bundle research results on climate change for certain regions and natural spaces as well as to prepare and communicate them in a comprehensible fashion. In this context each climate office represents the regional aspects of climate research based on the scientific expertise of the respective Helmholtz centre.

The Climate Office for Polar Regions and Sea Level Rise has furthered this important process of communication from the scientific community to the various segments of our society through various projects. Here are three examples.

For the Youth Forum of the 32nd German Church Day in Bremen pupils of three school classes at the Utbremen school centre developed along with the Climate Office the concept for a climate information tent that they also organised and managed together. The highlight for the pupils was an encounter and question and answer session with Mr. Angaangaq, the elder of the

Fig 2: Prof. Peter Lemke (Head of the Climate Science Research Division at AWI) and Mr. Angaangaq during a discussion with young people on the outside stage of the youth centre.
Photo: Renate Treffeisen, AWI

Kalaallit, indigenous people of Greenland belonging to the Inuit (Fig. 2). His family ranks among the traditional healers from Kalaallit Nunaat, as Greenland is called in the language of the indigenous people there.

Furthermore, the Climate Office was involved in developing the 'Concept study – Climate City Bremerhaven', contracted by the Bremerhaven municipal council. The objective of the study was to work out Bremerhaven's unique selling points in the field of climate competence, identify application-oriented potential for Bremerhaven and the region and formulate recommendations for additional measures and development steps. Its participation in the concept study is an example of AWI's involvement in local and regional climate activities. The Climate Office will also take part in the follow-up projects.

One final example: In March 2010 the Climate Office for Polar Regions and Sea Level Rise organised a two-day seminar in Berlin with the British Council there. They invited young participants and project managers from various programmes whose common focus is on 'youth leadership' in the Arctic (Fig. 3). The aim of the seminar was to determine how these programmes meet the requirements of training, commitment and communication. In addition to the seminar, there was an evening event at the British Embassy directed at the broad public. Prominent personalities from the fields of climate research, economics and social science discussed within this framework new insights regarding climate changes as well as the results of the World Climate Summit in Copenhagen.

Fig 3: Participants in the workshop 'Action for the Arctic' in Berlin
Photo: British Council Berlin

Fig 4: Prof. Dr. Peter Lemke in conversation with pupils from the Utbremen school in the climate information tent
Photo: Renate Treffeisen, AWI

Stationary and mobile infrastructure of the Alfred Wegener Institute in the Arctic and Antarctic

AWI maintains efficient infrastructure geared to the specific needs for research on the polar oceans and polar terrestrial regions. Scientists, engineers and technicians ensure the availability of this polar infrastructure and coordinate internationally the aircraft and ship expeditions which are conducted every year.

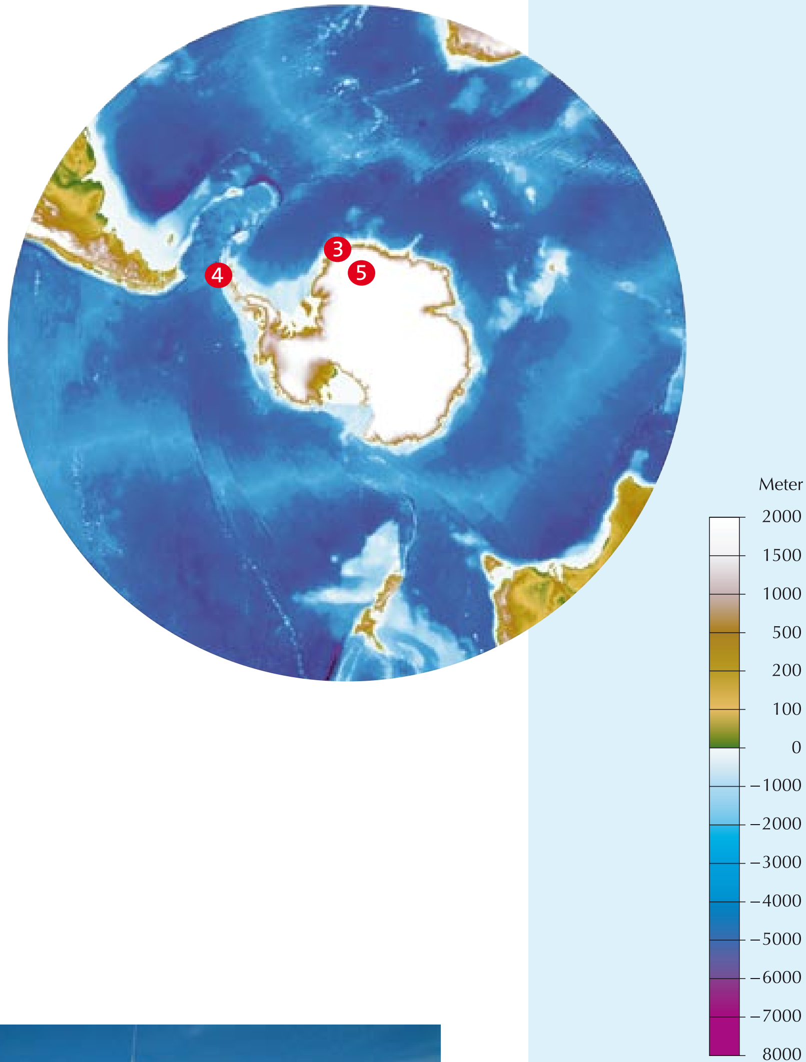
'Polarstern'
In an international comparison the research icebreaker Polarstern represents an outstanding research platform for the ice-covered polar oceans. Polarstern offers excellent research facilities for around 50 scientists, who are supported by 45 crew members. Laboratories and research equipment are designed for meteorological, oceanographic, chemical, biological and geological and geophysical work, thus enabling a multi-disciplinary approach to studies of the climate and ecosystem in the atmosphere, sea ice and ocean.

1 'German French Arctic Research Base (AWIPEV)'
Joint research station of AWI and the French polar institute Paul Emile Victor in Ny-Ålesund, Spitsbergen.
One of the major scientific tasks is the observation of the north polar stratosphere. Marine biological research is conducted mainly during summer. The new Kings Bay Marine Laboratory has been in use since June 2005, offering multiple opportunities for all kinds of biological and chemical studies in its various facilities. The station can accommodate marine biologists, ecologists, oceanographers as well as marine geologists and glaciologists.

2 'Samoylov Research Station'
Research station on the southern coast of Samoylov island in the middle of the Lena Delta near the Laptev Sea.
The research station Samoylov was built as a logistic base for long-term field investigations of permafrost formation and degradation, the transformation and emission of green house gases (methane, carbon dioxide) as well as the hydrology of the permafrost active layer and the formation and development of the Lena Delta.

'Polar 5'
Underway in the interest of science since 2007. The aircraft has wheel skis for use in ice-covered areas in the Arctic and Antarctic. Modern analytical instruments are available for research flights in the disciplines of geophysics, glaciology and atmospheric science. As from August 2011, a second research aircraft, the 'Polar 6', will complement the scientific and logistical operations of AWI in the polar regions.

3 'Neumayer Station III'
The Antarctic station began operation in 2009.
The building comprises research, service and living facilities and is built on a platform above the snow surface. The Station is located on the Ekström Ice Shelf, at the Atka Bay in the north-eastern Weddell Sea and is operated throughout the year. Nine people live and work there during the Antarctic winter: a doctor, a meteorologist, an atmospheric chemist, two geophysicists, an engineer, an electrician, a radio operator / an electronics engineer and a cook. The overwinterers stay for 14 to 15 months. For nine months, their only link to the outside world is by radio and internet.



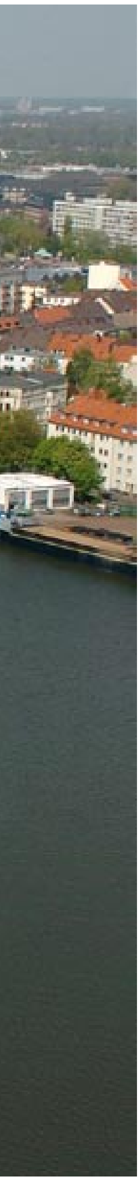
Topographic data:
ETOPO2v2 Global Gridded 2-minute Database
http://www.ngdc.noaa.gov/mgg/global/global.html,
rendered with:
The Generic Mapping Tools
http://gmt.soest.hawaii.edu
(Graphics: C. Schäfer-Neth)

4 'Dallmann Labor'
Research base at the Argentinian Jubany Station, King George Island, Antarctic.

5 'Kohnen Station'
Established in 2001 as a logistical base for ice core drilling in Dronning Maud Land.

Bremerhaven – Home of the Alfred Wegener Institute for Polar and Marine Research (AWI) in the Helmholtz Association

Due to innovative science and excellent research infrastructure, the institute has become one of the world's leading and internationally recognised centres for climate research in the polar regions as well as the oceans. The AWI also carries out scientific projects in temperate latitudes. However, the central research focus is on the frozen regions of the Arctic and Antarctic. The bio-, geo- and climate sciences work closely together to understand and unravel the forces and processes driving the climate system. A strong international network and the broad scientific expertise in particular are the AWI hallmark. The Research Centre includes the Research Unit Potsdam, the Biological Institute on Helgoland (BAH) and the Wadden Sea Station Sylt.



Contact persons at AWI

Imprint:
Alfred-Wegener-Institut
für Polar- und Meeresforschung
in der Helmholtz-Gemeinschaft
Am Handelshafen 12
27570 Bremerhaven, Germany
Phone +49(0)471-48 31-0
Fax +49(0)471-48 31-1149
Email: info@awi.de
www.awi.de

Climate Office for Polar Regions
and Sea Level Rise
Bussestr. 24
27570 Bremerhaven, Germany
Email: info@klimabuero-polarmeer.de
www.klimabuero-polarmeer.de

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Concept:
Prof. Dr. Peter Lemke, Climate Sciences Division
Dr. Renate Treffeisen, Climate Office for Polar Regions and Sea Level Rise
Claudia Pichler, Communications and Media Relations
Margarete Pauls, Communications and Media Relations (responsible)

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Alfred-Wegener-Institut
für Polar- und Meeresforschung
in der Helmholtz-Gemeinschaft

Am Handelshafen 12
27570 Bremerhaven, Germany
Telephone +49(0)471-48 31-0
www.awi.de

HELMHOLTZ
GEMEINSCHAFT