1 The world oceans, global climate drivers

> The oceans cover around 70 per cent of the Earth's surface. They thus play an important role in the Earth's climate and in global warming. One important function of the oceans is to transport heat from the tropics to higher latitudes. They respond very slowly to changes in the atmosphere. Beside heat, they take up large amounts of the carbon dioxide emitted by humankind.

Earth's climate system – a complex framework

> The Earth's climate is influenced by many factors, including solar radiation, wind, and ocean currents. Researchers try to integrate all of these influencing variables into their models. Many of the processes involved are now well understood. But interaction among the various factors is very complex and numerous questions remain unresolved.

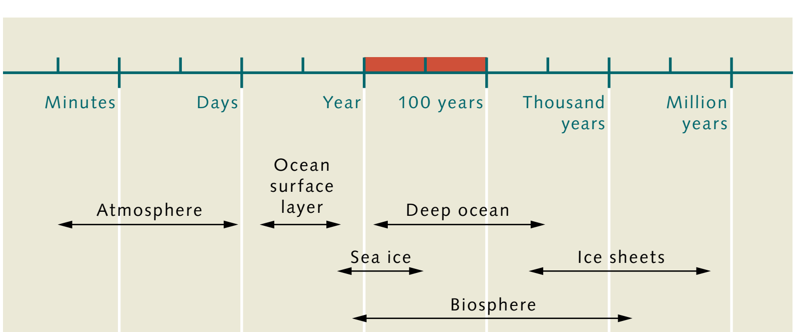
The inertia of climate

As we all learned in school, the world's oceans are one of the most important elements in the global climate system. But what does "climate" actually mean? The difference between weather and climate can be expressed in a single sentence: "Climate is what you expect; weather is what you get." This reveals a fundamental difference between weather and climate. Weather research is concerned with the formation, movement, and prediction of the individual elements of weather, such as a particular low-pressure system or a hurricane. Climate research, on the other hand, deals with the more comprehensive totality of low pressure systems and hurricanes, and is dedicated to addressing questions such as how many midlatitudinal storms or hurricanes will occur next year, or whether they will become more frequent or intense in the coming years as a result of global warming. So the term "weather" refers to short-term events in the **atmosphere,** while "climate" relates to longer time periods. For describing climate, as a rule, a time span of 30 years is generally used as a frame of reference.

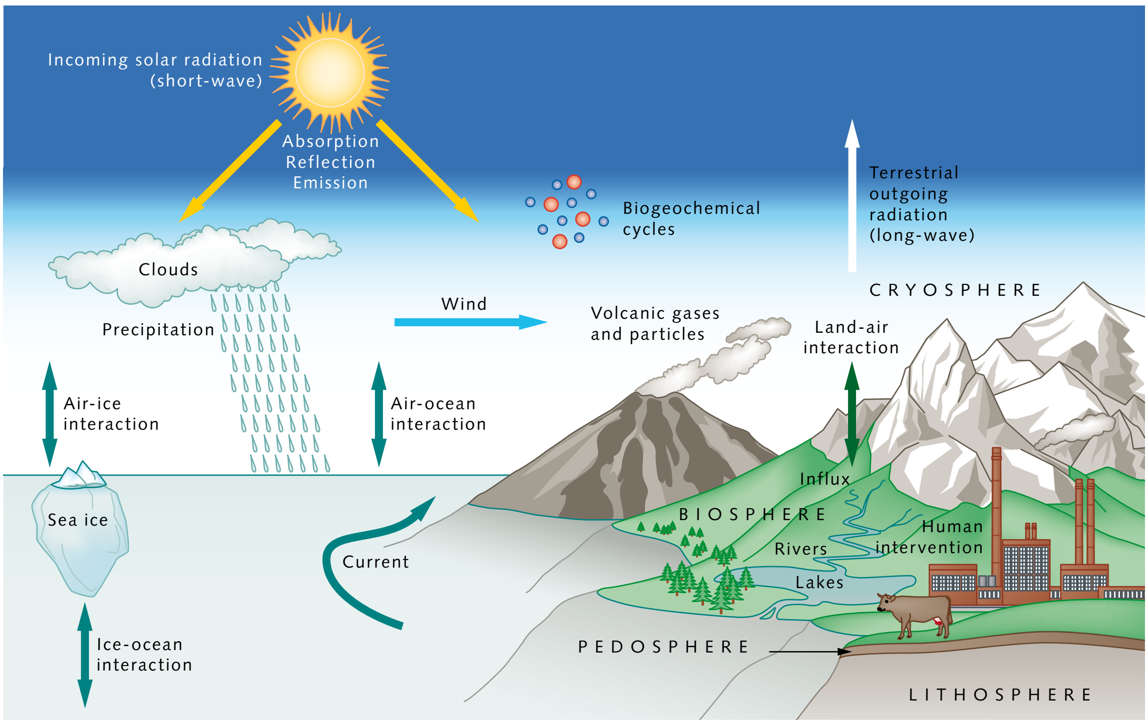
People mainly perceive climate change as changes in atmospheric variables, for example, variations in temperature or precipitation. In principle, due to its chaotic dynamics, the atmosphere itself can generate many natural climatic changes. One example of this is the **North Atlantic oscillation (NAO),** which significantly influences the climate over parts of Europe and North America. It is a kind of pressure fluctuation between the **Icelandic Low** and the **Azores High** that determines the strength of winter westerly winds across the North Atlantic. If these are strong, the result is mild and rainy weather in Western Europe; if they are weak it is dry and cold. These kinds of natural oscillations make it difficult to recognize anthropogenic climate changes due to an enhanced greenhouse effect.

The atmosphere is not an isolated system. It interacts with other components of the Earth system – the oceans, for example. But it is also in contact with the cryosphere (ice and snow), the biosphere (animals and plants), the pedosphere (soil) and the lithosphere (rocks). All of these elements together compose the climate system, whose individual components and processes are connected and influence each other in diverse ways.

These components all react to change at different rates. The atmosphere adjusts to the conditions at the Earth's surface such as ocean temperature or ice cover within a few hours to days. Furthermore, weather is variable and can only be predicted a few days in advance. In fact, it has been shown that the theoretical limit of weather pre-



1.1 > Different components of the climate system react to perturbations at different rates. The deep ocean, for example, is an important cause of the slow response of climate. The coloured area on the top scale represents the short time span of a human life.



1.2 > The climate system, its subsystems and relevant processes and interactions.

dictability is around 14 days. Currents in the deep sea, however, require several centuries to react fully to changing boundary conditions such as variations in the North Atlantic oscillation, which cause changes in temperature and precipitation at the sea surface and thus drive motion at greater depths. A large continental ice mass such as the Antarctic ice sheet, as a result of climate change, presumably undergoes change over many millennia, and without counteractive measures it will gradually melt on this time scale. The predictability of climate is based on the interactions between the atmosphere and the more inert climate subsystems, particularly the oceans. Within this scheme, the various components of the climate system move at completely different rates. Low-pressure systems can drift hundreds of kilometres within days. Ocean currents, on the other hand, often creep along at a few metres per minute. In addition, the individual components possess different thermal conductivities and heat capacities. Water, for instance, stores large amounts of solar heat for long periods of time.

Climate changes can be triggered in two different ways – by internal and external forces. The internal forces include:

- Changes in a single climate component, for example, an anomalous ocean current;
- Changes in the interactions between different climate components, for example, between the ocean and atmosphere.

Compared to these, the external mechanisms at first glance appear to have nothing to do with the climate system. These include:

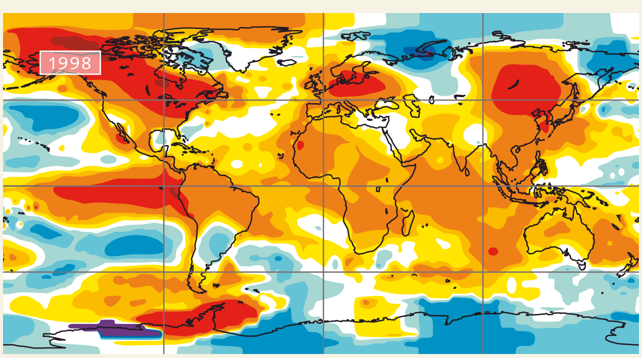
- The very slow drift of continents, which moves land masses into different climate zones over millions of years;
- The changing intensity of radiation emitted by the sun. The radiation energy of the sun fluctuates over time and changes temperatures on Earth;
- Volcanic eruptions, which inject ash and sulphur compounds into the atmosphere, influence the Earth's radiation budget and thus affect climate.

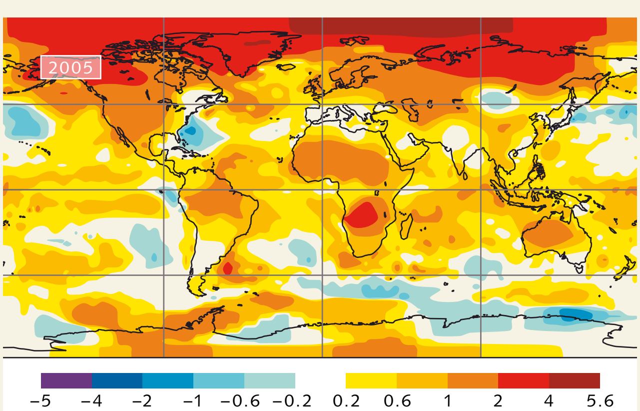
The difficulty of detecting anthropogenic climate change

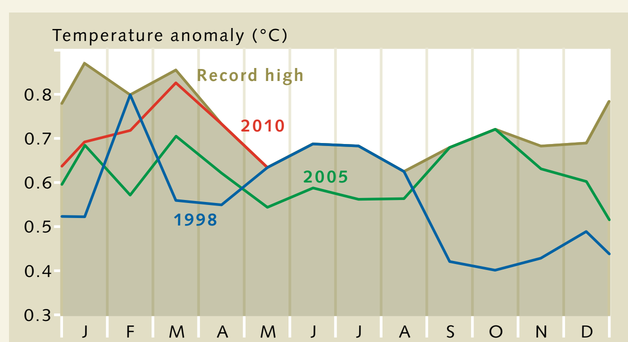
Climate fluctuations are not unusual. In the North Atlantic Sector, for example, it is well known that the average temperatures and winds can fluctuate on decadal time scales. Climate changes caused by humans (anthropogenic) also evolve over the course of several decades. The natural decadal changes and those caused by humans are therefore superimposed upon one another. This makes it difficult to assess the impact of humans on climate with certainty. In contrast to the dynamic North Atlantic region, the effects of climate change are easier to detect in more stable regions such as the tropical Indian Ocean.

There is no doubt that the oceans drive interannual or decadal climate fluctuations. Decadal fluctuations of Atlantic hurricane activity or precipitation in the Sahel correlate remarkably well with oscillations of ocean temperature in the North Atlantic. Although the precise mechanisms behind these decadal changes are not yet fully understood, there is general agreement that variations in the Atlantic overturning circulation play an important role. This hypothesis is also supported by the fact that Atlantic sea surface temperature anomalies occur in cycles of several decades, with a pattern which is characterized by an interhemispheric dipole. When the rate of northward warm water transport increases, the surface air temperature rises in the North Atlantic and falls in the South Atlantic. If it becomes cooler in the north and warmer in the south, it is an indication of weak ocean currents. The air-temperature difference between the North and South Atlantic is therefore a measure of the overturning circulation strength.

Modern climate models can simulate the present-day climate and some historical climate fluctuations reasonably well. These models describe the climate with satisfactory reliability, especially on a global scale. But for smaller geographical areas the models are less





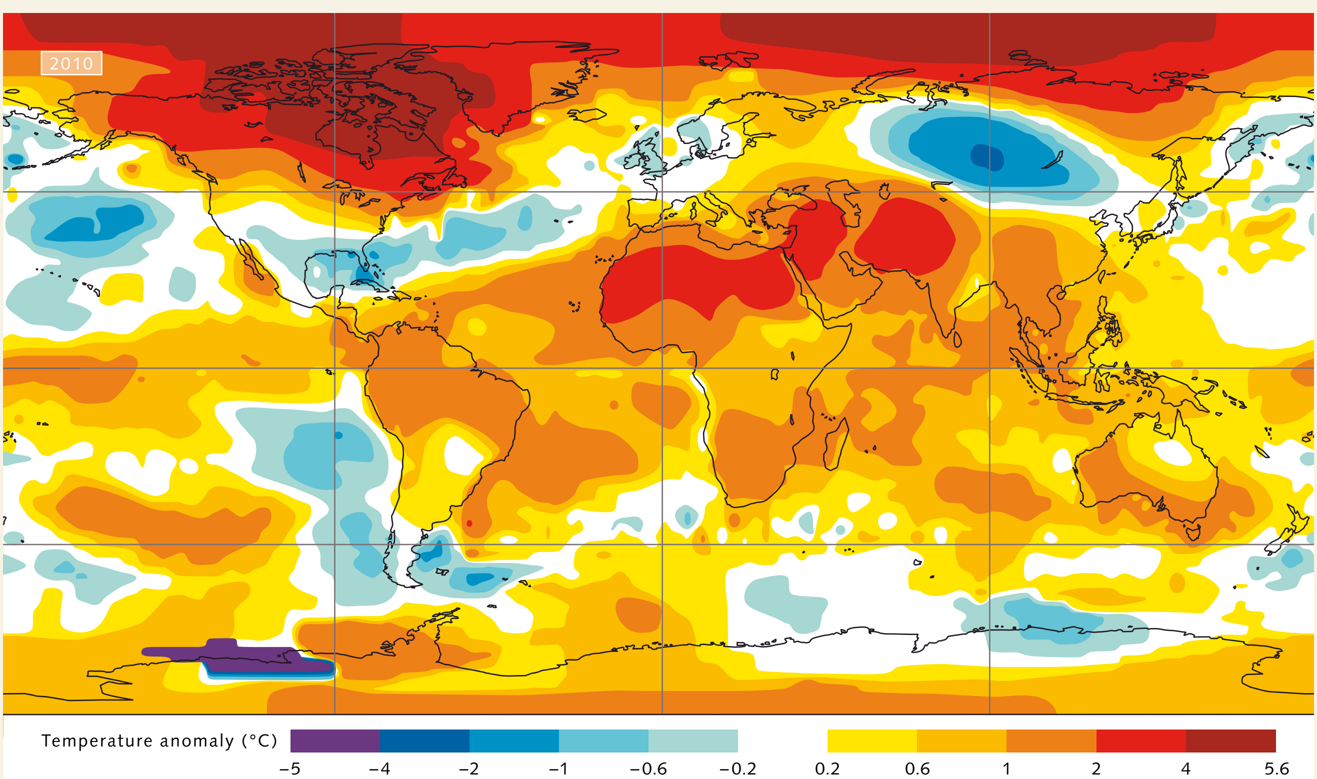


1.3 > Europe experienced an unusually cold beginning of the year 2010. But from a global perspective, the winter of 2010 was the third warmest in the past 131 years. If the first five months of the year are considered, then 2010 is actually the warmest, and it even reached the previous temperature record highs for the months of April and May (top). The years 1998 and 2005 have been so far the two warmest years in the annual mean (relative to the average of 1951 to 1980).

reliable. It is much easier to infer the globally averaged temperature than to predict the future precipitation in Berlin. Extensive measurement series are required to better understand regional climate. For many regions of the Earth, in the Southern Ocean for example, there are long time periods in the past with only a limited number of measurements. Today data are provided in these areas by satellites.

Many mathematical models now exist that can help to understand the impacts of human activity on climate. As one aspect, they simulate climate response to external natural and anthropogenic forcing, but they also reveal how climate interacts with the **biogeochemical** cycles such as the **carbon cycle** (Chapter 2). Climate research is thus developing into a more comprehensive study of the Earth system, and today's climate models are evolving into Earth system models. This is necessary in order to study the multiple interactions. For example, the impact of global warming on the **stratospheric** ozone layer can only be investigated when the chemical processes in the atmosphere are taken into account. Another example is acidification of the seawater (Chapter 2) due to uptake of anthropogenic CO_2 by the ocean.

No one has yet been able to predict how the warming and acidification of the ocean will influence its future uptake of anthropogenic carbon dioxide, upon which the carbon dioxide levels in the atmosphere and thus the future temperature change depend. There is a mutual interaction between the ocean and the atmosphere. To a large extent the ocean determines the intensity of climate change, and its regional expression in particular. On average, warming is taking place globally. But individual regions, such as the area of the Gulf Stream, may behave in different ways. On the other hand, the ocean itself reacts to climate change. Understanding this complex interplay is a task that will take years to accomplish.



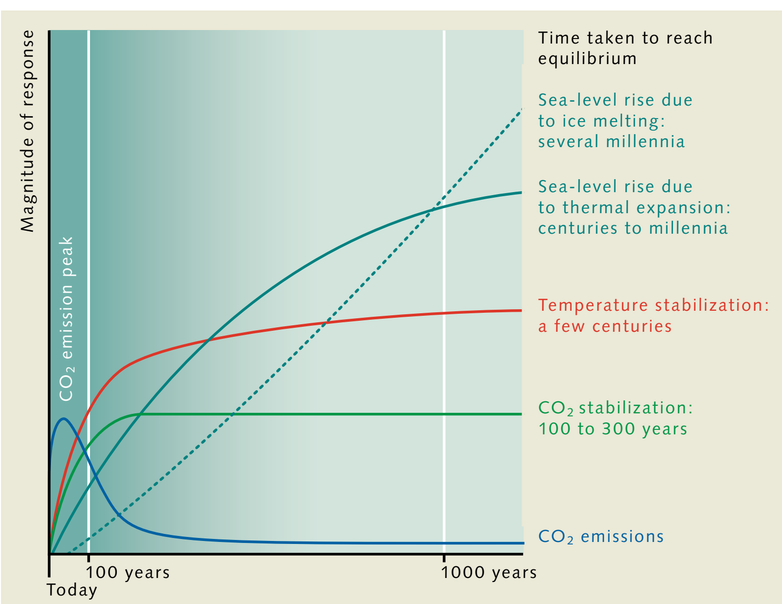
How humans are changing the climate

The human impact on climate has greatly increased over the past hundred years. We release vast amounts of climate-relevant trace gases into the atmosphere. This changes the radiation balance of the atmosphere and leads to global warming.

In addition to carbon dioxide, these trace gases include methane, nitrous oxide (laughing gas), halogenated fluorocarbons, perfluorinated hydrocarbons, and sulphur hexafluoride. But carbon dioxide (CO_2) is especially important for the Earth's climate system because the worldwide output is so enormous. It is released primarily through the burning of fossil fuels (oil, natural gas, and coal) in power plants, vehicle engines or in household heating systems. Its atmospheric levels have risen to almost 390 parts per million (ppm) today as compared to the pre-industrial value of 280 ppm. With this increase the temperature has also risen during the twentieth century. The internally driven changes in the oceans such as changes in the **Gulf Stream** also occur within a time frame of decades or a few centuries. These have a decisive influence on climate and on the concentration of greenhouse gases in the atmosphere because they are strongly involved in global mass cycles such as the carbon cycle. For example, CO_2 dissolves easily in water. However, the oceans have taken up about half of all the carbon dioxide produced by the burning of fossil fuels since the beginning of the industrial revolution, which has clearly dominated the natural variations. Whether the climate will change in the future, and by how much, can therefore be also deduced from the oceans.

Climate will change very slowly in the future because the oceans with their immense volumes of water react very gradually to change. Therefore, many but not all of the consequences of climate change triggered by human activity will only gradually become noticeable. Some of these consequences could actually be irreversible when certain thresholds are crossed. At some point it will no longer be possible, for instance, to stop the complete melting of the Greenland ice sheet and the resulting seven-meter rise of sea level. The position of the threshold, however, is not precisely known. But one thing is certain: Even if the emission of carbon dioxide were stabilized at today's levels it would not lead to a stabilization of the carbon dioxide concentration in the atmosphere, because carbon dioxide is extremely long-lived and the carbon dioxide **sinks**, mainly the oceans, do not absorb it as quickly as we produce it.

The situation is different for short-lived trace gases like methane (CH_4). If methane emissions were stabilized at the present level, the methane concentration in the atmosphere would also stabilize, because methane diminishes in the atmosphere at about the same rate as it is emitted. In order to maintain the carbon dioxide concentration at a given level, the emissions have to be reduced to a fraction of the present amounts.



1.4 > Even if it is possible to significantly reduce the emission of greenhouse gases, and CO_2 in particular, by the end of this century, the impact will still be extensive. CO_2 has a long life and remains in the atmosphere for many centuries. Because of this, the temperature on the Earth will continue to rise by a few tenths of a degree for a century or longer. Because heat penetrates very slowly into the ocean depths, the water also expands slowly and sea level will continue to rise gradually over a long period of time. Melting of the large continental ice sheets in the Antarctic and Greenland is also a very gradual process. Melt water from these will flow into the ocean for centuries or even millennia, causing sea level to continue to rise. The figure illustrates the principle of stabilization at arbitrary levels of CO_2 between 450 and 1000 parts per million (ppm), and therefore does not show any units on the response axis.

1.5 > To bring attention to the threat of global warming, the government of the Republic of Maldives held a meeting on the sea floor in autumn 2009 just before the Copenhagen summit.

A looming catastrophe

Long after the stabilization of carbon dioxide levels, the climate will still further continue to change because of its inertia. Climate models indicate that the near-surface air temperature will rise for at least a hundred years. Sea level will continue to rise for several centuries because seawater expands slowly as a result of the gradual warming of the deep sea, and because the continental ice sheets in the Arctic and Antarctic will probably react very slowly to the warming of the atmosphere, and the glaciers will continue to melt for many millennia. It will therefore be a long time before sea level achieves a new equilibrium. But scientists also believe it is possible that, if the warming is strong, the Greenland ice sheet could completely melt within this millennium and disappear into the ocean. The ice sheet could actually break apart and giant pieces fall into the sea. The enormous amounts of fresh water could cause a critical change in ocean circulation, for example, in the Gulf Stream. In an extreme scenario, sea level could rise by more than a metre per century, regionally by even more

The inertia of the climate system and the danger that the trend is irreversible should be sufficient reasons for forward-looking action. One should always keep in mind that the impacts of climate change that are measurable today do not yet reflect the total extent of climate change already caused by humans in the past. Humankind will only begin to feel them sharply in a few decades but has to take action right away.

Carbon dioxide and the greenhouse effect
The atmosphere is becoming more enriched in carbon dioxide (CO_2), or to be more precise, carbon dioxide and other climate-relevant trace gases. Initially they allow the incoming short-wave radiation of the sun to pass through. This energy is transformed to heat at the Earth's surface and is then emitted back as long-wave radiation. The gases in the atmosphere, like the glass panes of a greenhouse, prevent this long-wave radiation from escaping into space, and the Earth's surface warms up.

The great ocean currents – the climate engine

> Ocean currents transport enormous amounts of heat around the world. This makes them one of the most important driving forces of climate. Because they respond extremely slowly to changes, the effects of global warming will gradually become noticeable but over a period of centuries. Climate changes associated with wind and sea ice could become recognizable more quickly.

What drives the water masses

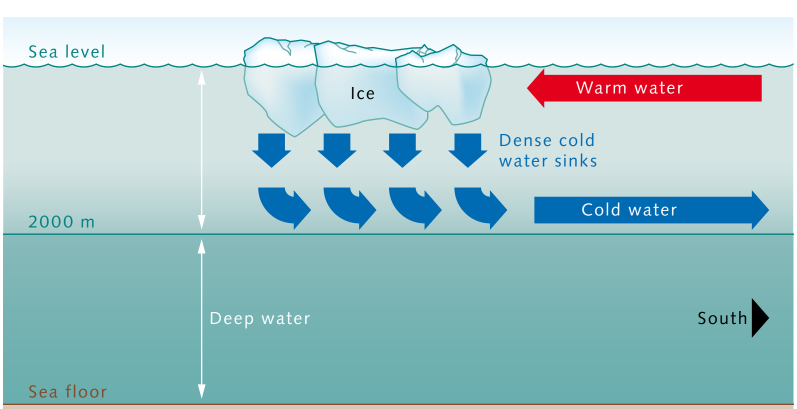
Water plays a central role in the climate system. Its density varies depending on salinity and temperature. Cold, salty water is heavy and sinks to great depths. This causes the circulation of millions of cubic metres of water in the ocean. This powerful phenomenon, which primarily occurs in a few polar regions of the ocean, is called convection.

The surface water in the North Atlantic region sinks to a depth of around 2000 metres due to convection. There it settles on an even denser deep-water layer from the Antarctic that extends down to the sea floor. As the cold and salty surface water sinks by convection, salty water flows in from nearby warmer regions, from the direction of the equator. This water is then cooled in the Arctic air and also begins to sink, so that the convection is continuous. Before sinking, the water absorbs enormous amounts of gases such as carbon dioxide at the sea surface, and then transports them rapidly to much greater depths. That is why the highest concentrations of carbon dioxide in the ocean are found in the convection areas.

The high carbon dioxide concentrations pumped into the water by convection have been shown to reach depths today of around 3000 metres. Carbon dioxide is transported relatively rapidly by convection to a depth of 2000 metres. In the North Atlantic the transport to greater depths takes significantly longer because carbon dioxide and other gases can only penetrate the deep water by slow mixing processes.

Low temperature and high salinity are the primary driving forces of convection. They pull the dense water of the polar regions downward, which drives a worldwide convection engine called thermohaline circulation (*thermo* – driven by temperature differences; *haline* – driven by salinity differences). The cold, salty water submerges primarily in the Labrador and Greenland Seas, and then flows southward toward the equator and beyond. Although convection only occurs locally in the polar regions, it propels thermohaline circulation, which spans the globe like a giant conveyor belt. Even the Gulf Stream and its branches are driven by convection and thermohaline circulation. Although wind also influences the transport of water masses, its contribution is significantly less.

But how do the water masses of different densities that drive ocean convection actually originate? Air temperature, evaporation and precipitation are among the



1.6 > The convection process in the North Atlantic: Cold, salty water sinks in the Labrador and in the Greenland Sea. This water forms a layer above the denser deep water from the Antarctic at a depth of around 2000 metres and flows toward the equator. Warmer waters from the upper ocean layers move into the convection area to replace the sinking water.

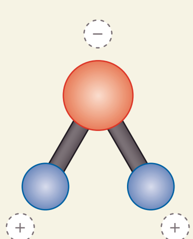
Water – a unique molecule

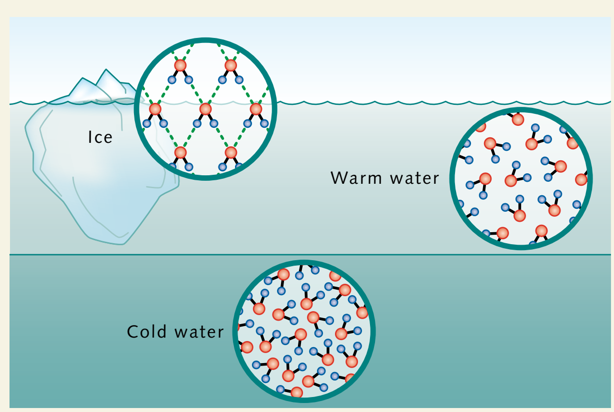
Water behaves differently from most other chemical compounds. In almost all substances the atoms and molecules move closer together as they get colder. They then solidify. Water, however, attains its greatest density at four degrees Celsius because the water molecules are packed closest together at this temperature. Many freshwater lakes have a temperature of four degrees at their deepest point because the heavy water sinks to the bottom. But surprisingly, to reach the solid ice phase, the water molecules again move farther apart. This phenomenon is referred to as the water anomaly. Ice is lighter and floats at the surface. This is seen in the large ocean regions at polar latitudes, which are partly covered by ice. The reason for this anomaly lies in the unusual properties of the water molecule (H_2O). Its oxygen atom (O) and the two hydrogen atoms (H) are asymmetrically arranged. This produces a dipole, a molecule with one negatively and one positively charged end.

Depending on the temperature, these dipoles align themselves into aggregates according to their charge, for example, in the formation of an ice crystal. The dipole character of water is a critical factor for climate. Because the water dipoles tend to hold together like small magnets, water reacts sluggishly to warming or cooling. In fact, water has the highest heat capacity of all liquid and solid substances with the exception of ammonia. This means that water can absorb large amounts of heat before it boils. Both, the freezing and boiling points of water (zero and 100 degrees Celsius, respectively), so much a part of our daily lives, are really rather unusual. If the water molecule were symmetrical (not a dipole), then water (ice) would melt at minus 110 degrees Celsius and boil at minus 80 degrees. The inertia of climate is a result of the high heat capacity of water in the first place.

Water influences climate not only in its liquid and solid states. H_2O in the form of water vapour in the atmosphere has a decisive impact on the heat budget of the Earth; water vapour alone is responsible for about two thirds of the natural greenhouse effect. In addition, it amplifies the impact of other substances on climate. For example, if the temperature rises as a result of higher carbon dioxide levels, then the water vapour content also increases because the warmer atmosphere can sustainably hold more water vapour. Because of its dipole molecule, water absorbs infrared radiation very efficiently. As a result, it approximately doubles the warming originally caused by carbon dioxide.

Another important property of water is its ability to dissolve salts, which significantly changes its density. The average salinity of the ocean is 34.7 parts per thousand (‰). At this salinity water has a greatest density of minus 3.8 degrees Celsius, which is below the freezing point of seawater with average salinity. This is, in fact, minus 1.9 degrees Celsius. So surface cooling can cause convection until ice is formed. This density trait is the engine for convection, one of the most important elements of the climate system; cold, salty water is heavy and sinks to great depths. It is replaced by water flowing in at the sea surface.





1.7 > The water molecule is asymmetrical and is therefore oppositely charged at its two ends (left). This is called a dipole. It thus behaves differently from other substances in many ways. Ice is less dense (top) and floats on the surface. Freshwater has its greatest density at four degrees (bottom), and sinks to the bottom. This is then overlain by warm water (middle). Salty water has different characteristics.

most important factors in the answer to this question. The freezing of water in the polar convection regions also plays a central role. Because ice only contains about five tenths of a per cent salt, it leaves behind a considerable amount of salt in the water when it freezes, which increases the salinity of the surrounding ocean water and thus increases its density. The water mass produced by convection in the Arctic is called the North Atlantic Deep Water (NADW).

The path of water into the deep ocean

There is no other area in the ocean where the surface water finds its way so quickly into the deep as in the convection areas, and at no other place do changes at the sea surface or in the atmosphere become so rapidly apparent in the ocean's interior, for example, in the increased carbon dioxide levels in the water as a result of higher carbon dioxide concentrations in the atmosphere. Convection connects two distinctly different components of the ocean: the near-surface layers that are in contact with the variable atmospheric fields of wind, radiation and precipitation, and the deep regions of the ocean. At the surface, currents, temperature and salinity fluctuate on a scale of weeks to months. But at greater depths the environmental conditions change at time scales of decades or centuries.

In the consistently warm oceanic regions of the tropics (the warm regions of the Earth between 23.5 degrees north and 23.5 degrees south latitude) and the subtropics (the regions between 23.5 and 40 degrees in the northern and southern hemispheres), there is no exchange between the surface and deep waters that is comparable to polar convection. This is because, averaged over the year, there is a net radiation excess of the surface-layer waters. The warm water, with a minimum temperature of ten degrees Celsius, has a relatively low density and floats as a warm layer on top of the deeper, colder water masses. The two layers are distinctly separated with no gradual transition between them. At the boundary where they meet there is a sharp temperature jump, and therefore also an abrupt density difference that inhibits penetration of the heat to greater depths. The warm surface layer has an average thickness of several hundred metres, which is relatively thin compared to the total depth of the oceans. In very warm ocean regions such as the western equatorial Pacific, there is hardly any vertical mixing at all. Nearer to the poles, however, there is more vertical mixing of the oceans and layering is less well-defined. Because there is no abrupt temperature and density change there, changes in the sea surface can be transmitted to the interior depths of the ocean. But the convection areas are still the express elevator to the deep.

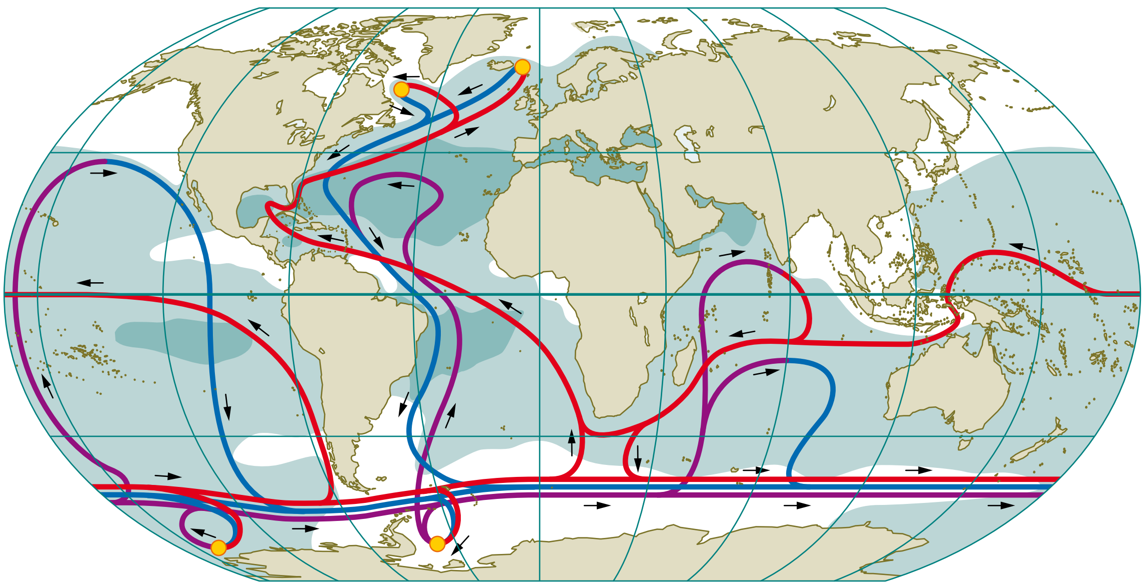
The global conveyor belt

Convection also occurs in the Antarctic regions. Because of their even higher salinity, the water masses produced here sink all the way to the sea floor. This is called the Antarctic Bottom Water (AABW), and it flows across the ocean floor halfway around the globe into the North Atlantic. The AABW is also the deep water layer that the thick intermediate NADW overlies when it sinks by convection. The NADW forms in the Greenland and Labrador Seas. Figure 1.8 schematically illustrates its flow path and the return flow of warm water in the near-surface layers, in the global conveyor belt of thermohaline circulation. The NADW, and especially the AABW, remain in the deep ocean for an amazingly long time. Radioactive carbon-isotope dating of the deep waters indicates that from the time of sinking into the deep until its return to the surface, a period of several hundred or even up to 1000 years will pass.

For most of this time the water remains in the colder deep regions of the thermohaline conveyor belt because there the flow rate is slow, at around one to three kilometres per day, due to its high density. The amount of water involved in this cycle is truly immense. Its volume is around 400,000 cubic kilometres, which is equivalent to about one third of the total water in the ocean. This is enough water to fill a swimming pool 400 kilometres long, 100 kilometres wide, and ten kilometres deep. The oceanic conveyor belt transports about 20 million cubic metres of water per second, which is almost 5000 times the amount that flows over Niagara Falls in North America.

Concerns about the breakdown of the Gulf Stream

There has been a great deal of discussion about the extent to which climate change could influence thermohaline circulation and its turnover processes in the Atlantic. After all, convection at high latitudes could be weakened by anthropogenic (caused by humans) warming of the atmosphere and the accompanying decrease in surface-



1.8 > The worldwide ocean currents of the thermohaline circulation system are extremely complex. The flow of cold, saline surface water (blue) downward and toward the equator can only be clearly recognized in the Atlantic. Warm surface water (red) flows in the opposite direction, toward the pole. In other areas the current relationships are not as clear-cut as they are in the Gulf Stream system (between North America and Europe). The Circumpolar Current flows around Antarctica, and does so throughout the total depth of the water column. The small yellow circles in the polar regions indicate convection areas. The dark areas are characterized by high salinity and the white areas by low salinity. Salty areas are mostly located in the warm subtropics because of the high evaporation rates here.

water density. Additionally the density will decrease as a result of lower salinity in the North Atlantic. Climate change will probably cause an increase in freshwater input through a number of pathways, which will affect convection and thermohaline circulation. One way would be by an increase in precipitation over both the continents and the ocean. Another would be the increase of freshwater run-off from the melting glaciers to the sea. Furthermore, because less ice forms when it is warmer, the salt concentration in the surface water would not be increased as much by this process.

Present-day climate models assume a weakening of the Atlantic turnover process by about 25 per cent by the end of this century. This would mean that less heat is transported northward from the tropics and subtropics. Ice-age scenarios such as those commonly proposed in the literature or films, however, are completely inappropriate, even if the circulation were to completely break down. The decreased influx of heat would be more than compensated by future global warming caused by the enhanced greenhouse effect. The Earth is warming up because of the insulating effect of carbon dioxide in the atmosphere. This temperature increase would offset the decreased northward heat transport from the tropics into the North Atlantic, and even exceed it on the adjacent land masses. When talking about the human impact on climate, scientists therefore tend to refer to a “warm age” rather than an “ice age”.

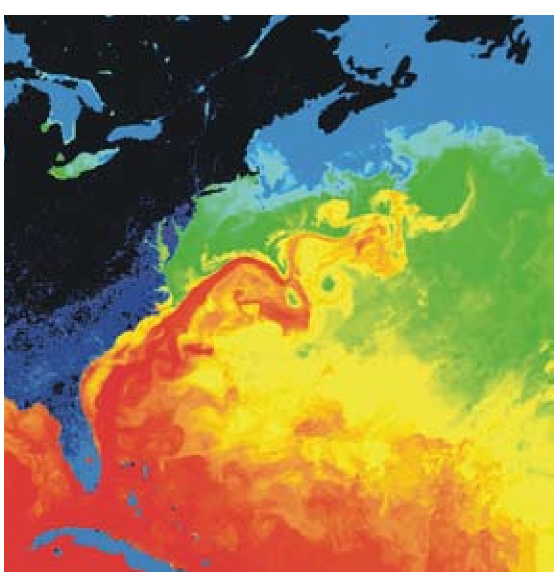
Eddies in the ocean – an important climate component

In addition to the large conveyor belt of thermohaline circulation, heat is also transported in the ocean by eddies, which are analogous to low-pressure systems in the atmosphere. But they are significantly smaller than the atmospheric low-pressure systems, which can often be several hundred kilometres wide. These mesoscale eddies form when water flows between regions with large density or temperature differences. They can be clearly recognized on satellite photographs. Investigations have shown that they not only occur at the ocean surface as, for example, in the North Atlantic area, but can also be located at great depths of thousands of metres, e.g. off the coast of Brazil. Because of their strong influence on the large-scale heat transport, these deep-sea eddies also play an important role in long-term climate processes.

The Coriolis force
The Earth's rotation causes all free linear motion on the Earth, such as air or water currents, to be diverted to one side. The diverting force is called the Coriolis force or Coriolis acceleration. It works in opposite directions in the northern and southern hemispheres. The Coriolis force is named after the French natural scientist Gaspare Gustave de Coriolis (1792 to 1843), who derived it mathematically.

Variable and dynamic – the influence of wind

Along with convection, winds also provide an important contribution in driving the ocean currents. In combination with the diverting force caused by the Earth's rotation (Coriolis force) and the shape of the ocean basins, winds determine the characteristic patterns of the worldwide system of surface currents. Especially striking are the large gyres that extend across entire ocean basins, for example between America and Europe. These surface currents include the Gulf Stream in the Atlantic Ocean, which is driven both by wind and the thermohaline force, as well as the Kuroshio in the Pacific Ocean, whose intensity just decreases with depth.



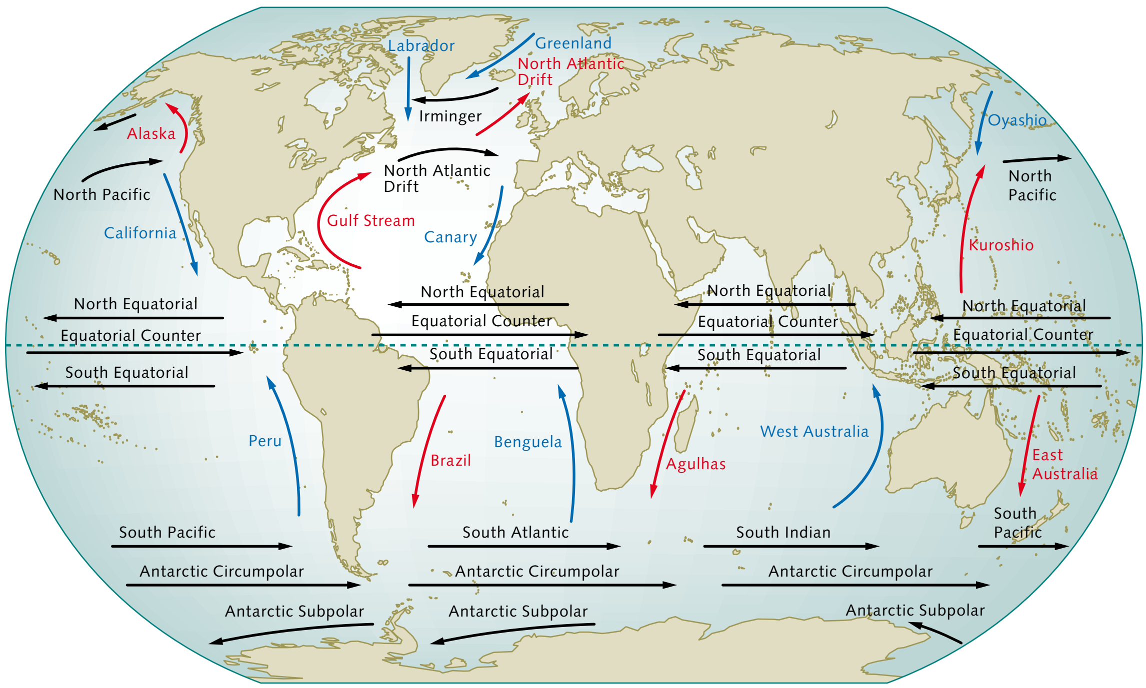
1.9 > Satellite photograph of the Gulf Stream and its eddies. Warm areas are red, cold areas are blue.

The Gulf Stream is a relatively fast current. Along the coast of North America it reaches a speed of around 3.6 kilometres per hour at the sea surface, which is a casual walking speed. It extends down to a depth of around 2000 metres, where the speed is around ten times slower because the influence of the wind is less and the density of the water is greater. Nevertheless, the wind can in fact have a direct influence down to great depths. Typical wind conditions can change for extended time periods. For example, the normally steady **trade winds** can blow from a different direction for months at a time, causing changes in the upwelling of water masses, and creating waves and currents in the ocean's interior that resonate at depth for decades. These waves can also change the ocean temperature and thus also the regional climate. From satellites these waves are perceived as slowly moving ups and downs of the ocean surface.

Furthermore, in certain regions the prevailing winds cause persistent upwelling and downwelling motion. In some areas the winds drive surface waters away from the land masses, allowing cold water from greater depths to rise in its place. The surface-water temperatures in these areas are therefore especially low. Important upwelling regions are often found on the western margins of continents where the winds blow parallel to the coast (Chile, California, Namibia). In the southern hemisphere, for example, because of the Coriolis force, the water is pushed to the left away from the coast when the wind is blowing from the south. This produces a rolling motion in the water, whereby the water on the surface moves away from the coast and water rises to replace it from below. This upwelling water is usually rich in nutrients, which is why many upwelling regions are also abundant with fish.

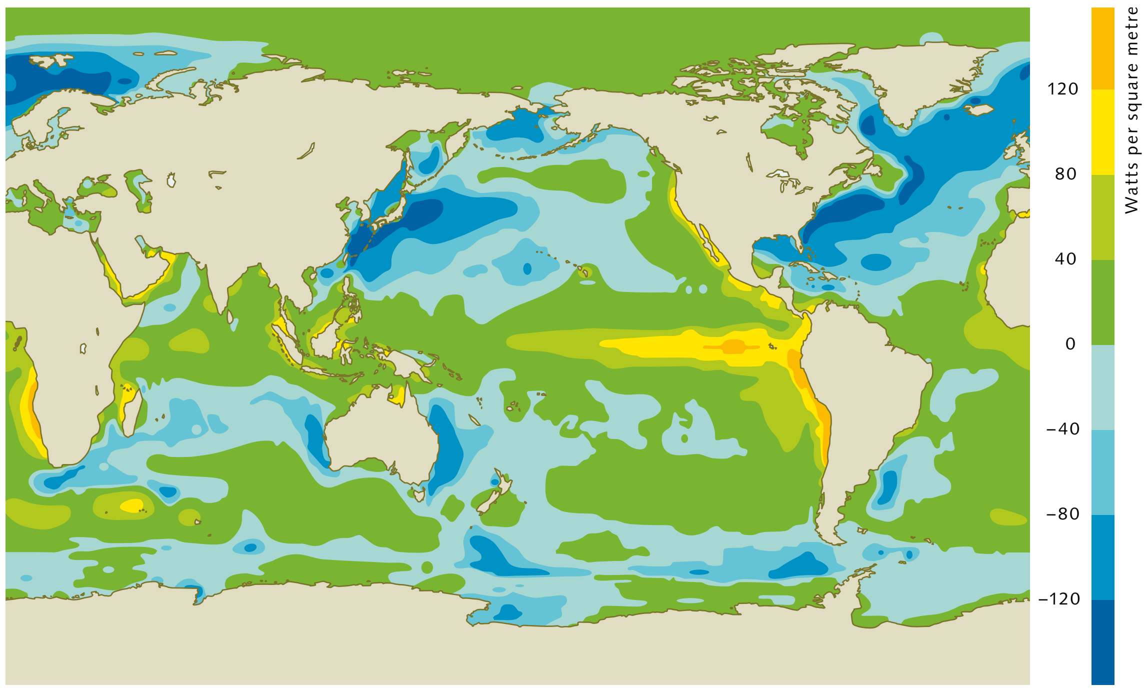
The ocean – a global storehouse for heat

In addition to huge masses of water, large ocean currents also transport enormous amounts of heat around the globe. Similar to the way the water tank in a heating sys-



1.10 > The world's large ocean currents are also influenced by the prevailing winds. Warm ocean currents are red, and cold currents are shown in blue.

tem stores heat from the solar installation on the roof, the oceans are an immense heat reservoir that retains energy from the sun over a long time. The large ocean currents transport this heat for thousands of kilometres and, as illustrated by the example of the Gulf Stream, significantly influence the climate in many regions of the world. In the warm tropics and subtropics up to a latitude of around 30 degrees, more heat arrives at the Earth's surface on a yearly average than it releases. In the higher latitudes, and extending to the poles, the opposite relationship exists. As a result the atmosphere and the oceans transport energy northward and southward from the equator to compensate for the imbalance. In some tropical regions, such as the eastern Pacific, the ocean gains more than 100 watts of heat per square metre, which is about what a hot-water tank produces to keep an apartment comfortable. In the higher latitudes the ocean releases heat. The areas of greatest heat loss are off the eastern coasts of North America and Asia and in parts of the Arctic, with values of up to 200 watts per square metre. In the North Atlantic and North Pacific regions the oceans release heat on an immense scale. The beneficiaries of this heat are those regions, including Europe, toward which the large current systems transport the warm water. The giant ocean currents transport a maximum amount of heat of just under three petawatts (quadrillion watts) to the north, which is around 600 times that produced by all the power stations worldwide. But the atmosphere also contributes to the energy balance between the tropics and the colder, higher latitudes. It transports an additional 2.5 to three petawatts of heat, resulting in a total northward transport of 5.5 to six petawatts. At European latitudes, heat transport in the atmosphere takes place through propagating low-pressure systems. In the Atlantic Ocean, however, the currents are more controlled and transport heat directly to the north. Here, warm water from the tropics flows northward far into the Arctic Ocean, where the water cools and releases heat into the environment. When it cools, the density increases. It sinks to greater depths and flows southward. The Atlantic current system transports enormous amounts of heat to the north through this thermohaline process and greatly exceeds the share transported by the wind-driven ocean circulation.



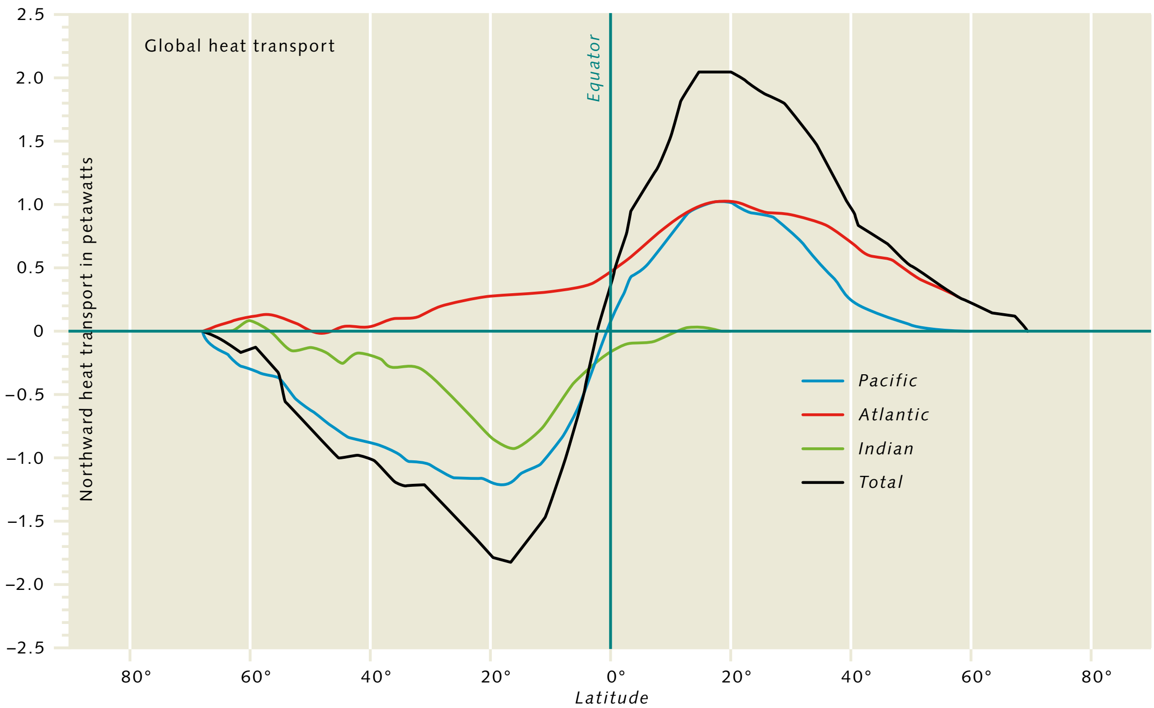
1.11 > Heat exchange between the atmosphere and the sea surface (in watts per square metre) is very variable depending on the ocean region. Positive values indicate absorption of heat by the ocean, which is characteristic of the tropics, and negative values indicate a heat loss, which is typical for the northern latitudes. In the high arctic regions, however, heat loss is relatively low because the sea ice acts as an insulating layer and prevents heat escaping from the water.

The Atlantic and Pacific Oceans each carry around one petawatt of heat northward from the tropics and subtropics. By comparison, the share moved by the Indian Ocean is negligible.

In this system the Atlantic has a unique function among the world's oceans. It is the only ocean basin that transports heat northward throughout its length, even in the southern hemisphere. Europeans all benefit from the northward trend, thanks to the Gulf Stream and the North Atlantic Current. The climate in the region of the North Atlantic is comparatively mild, especially in northwest Europe, including Germany. The winters in other regions at the same latitude are notably colder. In Canada, for example, the winter temperatures are around ten degrees Celsius lower than in Western Europe. But it is not the ocean circulation alone that causes the mild climate. Air currents also contribute significantly to this phenomenon. The distribution of mountain ranges, particularly the Rocky Mountains, which run from north to south along the west coast of North America, together with the influence of the Coriolis force, causes the formation of very stable, large-scale vortices in the atmosphere called standing planetary waves. Such a vortex lies above the USA because the Rocky Mountains act as an obstacle to divert large air masses. As a consequence the winds are predominantly westerly over the Atlantic carrying relatively mild air to northwest Europe, and fend off the cold from the east.

The uncertain future of sea ice

Sea ice in the Arctic regions has a significant impact on heat exchange between the atmosphere and ocean, because it acts as an insulating layer to prevent heat from



1.12 > Oceans contribute to the global transport of heat with different intensities. In the southern hemisphere, only the Atlantic transports heat to the north (positive values). The equator lies at zero degrees. The Atlantic and Pacific each carry around one petawatt of heat as far as 20 degrees north latitude. Further to the north, the Atlantic carries more than the Pacific. The Indian Ocean, on the other hand, makes a negligible contribution to northward heat transport.

escaping from the water. Considering how large the area of ice is, it is clear that it must have an impact on the global climate.

In the Arctic Ocean the sea ice, which is commonly called pack ice, has an average thickness of three metres. In the Southern Ocean it averages around one metre. The total area of sea ice expands and recedes with the seasons. On a yearly average around seven per cent of the oceans (about 23 million square kilometres) is covered with ice, which is equal to about three times the size of Australia. By comparison, the ice masses on land are relatively stable. They permanently cover around ten per cent of the land surface (14.8 million square kilometres). Scientists call the ice-covered areas of the Earth the cryosphere. In addition to land and sea ice, this also includes the shelf ice, the parts of continental ice sheets that extend into the ocean. Changes in the sea ice, including its extent, areal coverage, thickness, and movement, are caused by dynamic processes such as ocean currents and by **thermodynamic processes** such as freezing and melting. These, in turn, are influenced by solar radiation as well as the heat flux at the sea surface.

One of the most conspicuous and important characteristics of climate fluctuations is the change in sea-ice extent in the polar regions. During some winters the Arctic sea ice extends much further to the south than in others. Geophysicists consider the sea ice to be simply a thin, discontinuous layer on the polar oceans that is driven by winds and ocean currents, and is variable in thickness and extent. Sea ice forms a boundary between the two large components of the Earth system, the atmosphere and the ocean, and very significantly influences their interaction. Sea ice has a strong reflective property, called albedo, and it reflects a considerable amount of the

1.13 > As a rule, icebergs consist of freshwater or contain only small amounts of salt. Because of their slightly lower density compared to seawater, a small fraction extends above the water. The largest part is below the surface.

incoming sunlight. This effect is enhanced when the ice is covered with snow. The sea ice therefore influences the radiation balance of the Earth and thus plays an important role in the climate system.

The impact of sea ice on climate is further amplified by its insulating effect between the atmosphere and ocean. It inhibits the exchange of heat and wind energy between the atmosphere and ocean considerably. The atmosphere is therefore much colder above the sea-ice surface than above the open ocean. This has the effect of increasing the air-temperature difference between the tropics, subtropics, and the polar regions. In warmer regions the air has a greater tendency to rise, which lowers the air pressure significantly. By contrast, in very cold regions the air is heavier, and high pressure zones are created. Accordingly, the compensating air flow between high and low pressure areas is strong and, in concert with the Coriolis force, creates stronger westly winds in the middle latitudes. Of course, sea ice also influences convection processes in the ocean, and thus the formation of deep and bottom water. Sea ice therefore plays an important role in the large-scale ocean circulation, especially with regard to thermohaline circulation.

It is not yet known how global warming affects the formation of sea ice and the related processes. Ice melts when it becomes warmer. But it is difficult to predict what effect this has on the currents. In any case, all climate models predict an acceleration of warming in the Arctic with a continuing rise in trace-gas concentrations.

In addition, observations indicate a clear decrease in Arctic sea-ice cover in recent decades. This is partly related to a positive feedback mechanism called the ice-albedo feedback. Light surfaces have a very high albedo. When the sea ice retreats as a result of global warming, albedo decreases and more solar energy is available, which leads to additional warming, and melts more ice. This process primarily occurs at the margins of the sea ice. Similar to a spot of grass on the edge of a patchy snow cover, the seawater at the margins of the ice warms more rapidly, and the ice thaws faster there. The further the ice retreats, the larger the area of the open, relatively dark sea surface becomes. The melting is thus amplified. The shrinking of sea ice could therefore amplify climate change in the future. Ironically, this would provide people with something that they have been wanting for a long time: the opening of a northern seaway from Europe across the Arctic to Asia – the Northern Sea Route. In recent years the ice has retreated at such a rate that Arctic waters along the north coast of Russia could be navigable year-round by commercial ships in the future. The route is several thousand kilometres shorter than the trip through the Suez Canal. In the early autumn of 2009 a Bremen shipping company became one of the first private companies in the world to navigate the Northern Sea Route with a merchant vessel. But the negative consequences of climate change will presumably outweigh the advantages of a navigable northern route. There is, for instance, a substantial negative impact on Arctic animals such as the polar bear, whose habitat is melting away.

The large ocean currents and their driving forces have already been intensively investigated, but there are still many unanswered questions in the fine details. For example, thermohaline circulation, with the interplay of its driving factors, has not yet been completely explained. Different mathematical models have produced different conclusions. All models use the same equations, variables, and input parameters. But it is difficult to accurately estimate climate influences at scales of a few kilometers or even smaller and to apply them correctly within the large, global models.

Conclusion

Time to act

Climate change will affect the oceans in many ways, and these will not be limited to just altering the currents or heat budget. Increasing carbon dioxide concentrations in the atmosphere are accompanied by higher concentrations in the oceans. This leads to increased carbonic acid levels, which acidifies the water. At present the consequences for marine animals cannot be predicted.

Similarly, very little is known about how the weakening of thermohaline circulation or the Gulf Stream will affect biological communities, such as crab or fish larvae which are normally transported by currents through the oceans. The dangers associated with rising sea level were again stressed during the climate conference in Copenhagen in 2009. Specialists today largely agree that sea level will rise by around one metre by the end of this century if the worldwide emission of greenhouse gases by humans continues to increase as rapidly as it has in recent decades. This will be fatal for island nations like the Maldives, which inundation could render uninhabitable within a few decades. The fact that scientists cannot yet predict with complete certainty what the future effects of climate change will be is not a valid argument for inaction. The danger is real.

Human society needs to do everything in its power to bring the climate-change experiment to an end as soon as possible. The climate system reacts slowly to changes caused by human intervention, so there is a strong possibility that some changes are already irreversible. This risk should provide sufficient motivation for forward-looking action to significantly reduce the emission of climate-relevant gases. There is no time to lose in implementing climate protection measures. There are many indications that the most severe consequences of climate change can still be avoided if investment is made today in low-carbon technology. It is time to act.

Table of figures chapter 1

cover: mauritius images/Bluegreen Pictures, p 2: plainpicture/Daniela Podeus, p. 6 from top: Nick Cobbing, Steve Gschmeissner/Science Photo Library/Agentur Focus, Seth Resnick/Getty Images, U.S. Coast Guard/digital version by Science Faction/Getty Images, David B. Fleetham/SeaPics.com, p. 7 from top: Arctic- Images/Corbis, Steve Bloom/Getty Images, Justin Guariglia/Corbis, 2009 George Steinmetz/Agentur Focus, US Navy/action press, pp. 8–9: Nick Cobbing, Fig. 1.1: after Meincke und Latif (1995), Fig. 1.2: maribus, Fig. 1.3: NASA Goddard Institute For Space Studies, Fig. 1.4: after IPCC (2001), Fig. 1.5: action press/Ferrari Press Agency, Fig. 1.6: maribus, Fig. 1.7: maribus, Fig. 1.8: after Meincke et al. (2003), Fig. 1.9: NASA, Fig. 1.10: maribus, Fig. 1.11: after Barnier et al. (1994), Fig. 1.12: after Trenberth und Solomon (1994), Fig. 1.13: [M], Bryan & Cherry Alexander/Arcticphoto/laif

Publication details

Project manager: Jan Lehmköster
Editing: Tim Schröder
Copy editing: Dimitri Ladischensky
Editorial team at the Cluster of Excellence: Dr. Kirsten Schäfer, Dr. Emanuel Söding, Dr. Martina Zeller
Design and typesetting: Simone Hoschack
Photo-editing: Petra Kossmann
Graphics: Walther-Maria Scheid
Printing: Druckhaus Berlin-Mitte GmbH
Paper: Recysatin, FSC-certified

ISBN 978-3-86648-012-4
Published by: maribus gGmbH, Pickhuben 2, 20457 Hamburg

www.maribus.com