Deutsches Klima Konsortium

Konsortium Deutsche Meeresforschung

The Future of the Gulf Stream Circulation

Facts and background information from the research community

This brochure provides a clearly understandable overview of current scientific knowledge about the Gulf Stream circulation: researchers classify confusing and often contradictory information that is discussed by the general public. It thus constitutes an orientation of plausible future scenarios and relevant research questions.

The northern European climate is fairly mild compared to that in northeastern Canada, although both regions are approximately at the same geographic latitude. One of the reasons for this is the Gulf Stream circulation. Rising greenhouse gas emissions in the next few decades may considerably weaken the Gulf Stream circulation. This would definitely have severe consequences for the climate, sea level, the carbon cycle and marine ecosystems. The effects would not be confined to the North Atlantic area, but would also be perceptible in many regions of the world.

Current measurements in various regions of the Atlantic and simulations with realistic ocean models have shown a relatively stable Gulf Stream circulation for the last two decades. In this brochure, we will demonstrate why this is no reason for complacency. We use the latest measurements, describe the scientific methods, and explain why it is so difficult to interpret the limited available data and understand how the Gulf Stream circulation works.

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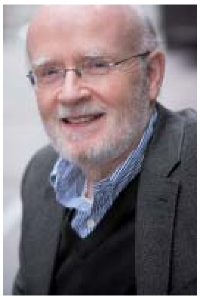
Foreword



Plant and microbial life on land and in the oceans provides our planet with oxygen. However, life on earth and human societies depend not only on oxygen, but also on a specific temperature range. It is primarily the “right” temperatures that have permitted the evolution of animal, plant, and human life. Temperature extremes, however, have contributed to crises in evolutionary history and shaped their course. Temperature extremes also endanger human life – just remember all the heat-related deaths in western Europe in 2003.

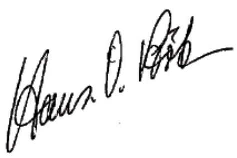
We could describe the Gulf Stream circulation as Europe’s air-conditioning system since it ensures pleasant temperatures and attenuates temperature maxima and minima.

Countless scientific papers as well as feature articles, science fiction, and movies address the “Gulf Stream phenomenon” – more than 13,000 publications in English bear its name in their title. The study of the Gulf Stream combines various scientific disciplines such as oceanography, biology, and climate modeling, and is of concern to decision-makers in politics and society.

Today, the Gulf Stream circulation still appears to be a constant in terms of space and time. However, like the entire Earth system, it is sensitive to apparently small changes in environmental conditions. In the face of climate change, we must be concerned about the Gulf Stream’s stability and, hence, about an important basis for the health of ecosystems and humans, as well as for prosperity and peace in Europe. Will the Gulf Stream as we know it survive? This is just a part of the issues and challenges that climate change produces for life on earth and human welfare.

In general, the significance of the oceans for the climate and the future of humankind is increasingly gaining the attention of politics and the general public. As co-chair of the working group on climate impact of the Intergovernmental Panel on Climate Change (IPCC), I am currently supervising two special reports directly concerned with changes in the oceans and the climate impacts on humankind and the environment. Furthermore, the Federal Ministry of Education and Research devoted its Science Year 2016*17 to “Seas and Oceans”.

The planet’s largest habitat still has many research-related questions for us – questions that we are only able to answer gradually, by employing steadily improving technology. This will make the extent to which our life depends on an intact ocean increasingly evident.



Hans-Otto Pörtner, Co-Chair of Working Group II “Impact, Adaptation, and Vulnerability”, IPCC

1. The significance of the Gulf Stream circulation

The Gulf Stream circulation has been in the public eye for many years. This is mainly due to its significance for the European climate and to the fact that most climate models predict a significant slowdown in the current system in the 21st century, should greenhouse gas emissions by humans and the consequential climate change continue unabated.

The Gulf Stream circulation transports warm, relatively salty water from the subtropics to the Arctic, thus contributing to northern Europe's moderate climate. It affects Germany as it does Norway, with its year-round ice-free harbors, or the western coast of Spitsbergen, which has no sea ice for several months of the year despite its extreme northern location.

What do we mean by Gulf Stream circulation? What do we know about it? How has it changed in the past and why? What is the current state of the circulation? And how will it develop in the future? These are the questions we want to answer in this brochure. We will also show why we only have fragmentary information about the ocean system to date, and why it is so difficult to come to a conclusion on the future of the Gulf Stream circulation and, hence, on the future of Europe's climate.

"Human influence on the climate system is clear." This is the key message in the Fifth Assessment Report of the IPCC, published in 2014. This conclusion is based, among other things, on the systematic temperature measurements available for many regions of the earth since 1850: the global mean temperature indicates a clear warming trend since the beginning of the 20^{th} century. It has also been adequately proven that humankind is the major cause of the temperature increase due to its emission of large amounts of greenhouse gases, such as carbon dioxide, into the atmosphere.

Circumstances are not nearly as clear in parts of the oceans, particularly in the Gulf Stream circulation. Insufficient data, the high complexity of ocean dynamics, and the resulting deficits in climate models currently do not permit reliable conclusions on the degree of human influence and to predict with high accuracy the future development of the Gulf Stream circulation. The past decades have shown no obvious trend, but rather a surprisingly large natural variability.

2. The Atlantic current system

Scientifically speaking, only the section along the eastern coast of North America constitutes the Gulf Stream. The entire current system in the upper ocean layers stretching from the Florida Strait through the North Atlantic to the Arctic is called the Gulf Stream circulation.

Various currents cross the oceans and thus affect the physical, chemical, and biological state of the oceans. The Gulf Stream circulation constitutes a particularly important current system. A whole network of ocean currents, which can be roughly divided into warm surface currents (red) and a cold deep branch (blue) – as illustrated in Figure 1 – permeates the Atlantic. Scientifically speaking, only the section along the eastern coast of North America constitutes the Gulf Stream, even though the name is used colloquially to refer to the entire current system in the upper ocean layers stretching from the Florida Strait through the North Atlantic to the Arctic. This band of currents forms the warm surface currents in the Atlantic circulation, which we call the Gulf Stream circulation.

Figure 1: Simplified illustration of the currents in the Atlantic. Warm near-surface currents are red, cold deep currents blue.

The Gulf Stream circulation is one of the strongest current systems of the World Ocean. Water flows northward along Florida at a rate of approximately 32 million cubic meters per second (1 million m^3/s = 1 Sverdrup [Sv]), transporting about 30 times the amount of water of all the rivers on earth. On its path towards the Arctic, the current grows even larger and reaches approximately 150 Sv. A considerable part, however, flows back south in the Subtropical Gyre, leaving about 30 Sv to continue making its way further northward. The current bifurcates once again and nearly one-third flows into the Norwegian-Greenland Sea and into the Arctic Ocean.

What drives this gigantic current system? The Gulf Stream circulation is powered firstly by winds and secondly by differences in temperature and salinity, the so called thermohaline forcing: the colder and saltier the water, the denser and heavier it is.

The tropical water flowing northward, which is warm and salty, cools down, becoming denser in the process. In a few places, the surface water becomes denser than the water at depth. It sinks and flows back southward as a deep current (Figure 1). Cooling alone cannot achieve sufficiently high densities for the water to sink and, consequently, for a vertically overturning circulation (Figure 2). The water must also be salty enough. The Gulf Stream circulation itself transports this salt. The high salinity is one of the reasons why water in the Northern Hemisphere only sinks in the North Atlantic.

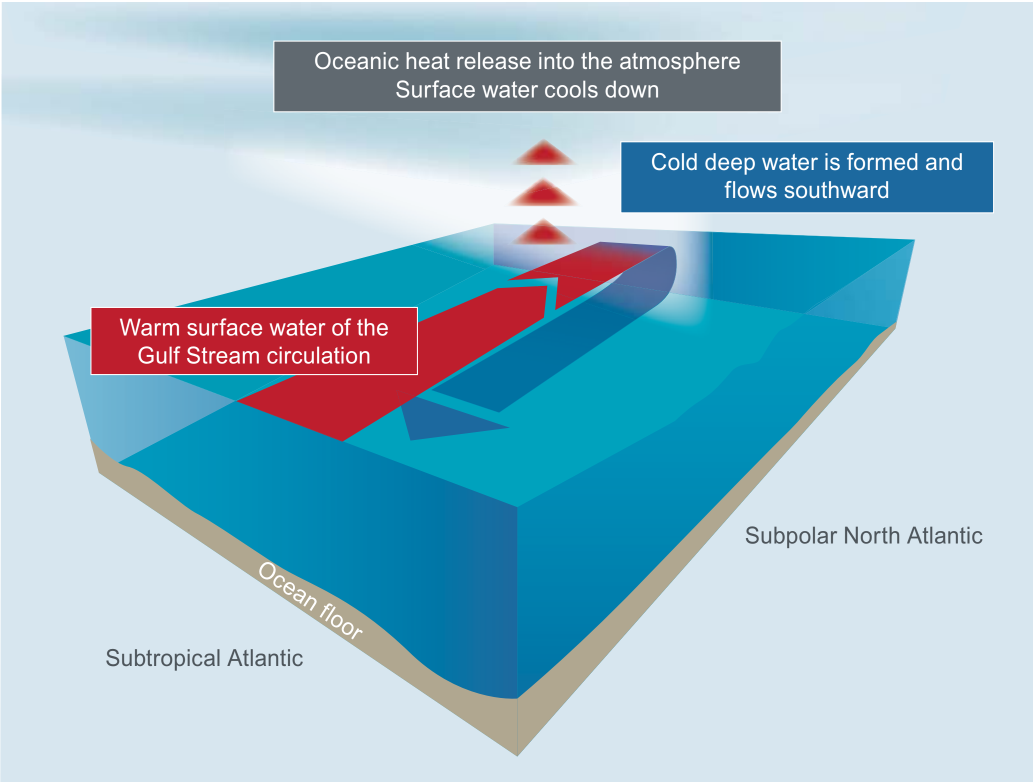


Figure 2: Schematic illustration of the circulation driven by changes in temperature and in salinity (hence, "thermohaline"), called overturning circulation.

The deep branch of the overturning circulation (shown in blue in Figure 1) is fed from two sources: the Labrador Sea and the Norwegian-Greenland Sea. In the Labrador Sea, which is situated between Greenland and Canada, strong winter cooling can cause water masses to sink up to 2,000 meters deep. Water originating from the Norwegian-Greenland Sea fills the layers below. It crosses the sea-floor ridges between Greenland and Scotland and plunges to the ocean floor in gigantic waterfalls. This large volume of about 30 Sv of cold deep water flows southward along the American coast. Part of the deep water reverses, leaving approximately 18 Sv to flow into the tropics and then into the South Atlantic.

Discussions about human influence on the Gulf Stream circulation are generally meant to be about the overturning circulation.

The overturning circulation is of fundamental importance for the climate because it transports heat from the south to the north on the surface of the entire Atlantic. The maximum heat transport takes place in the subtropics and is approximately 1.2 million gigawatts. The energy output drops by half in the transition from the subtropical to the subpolar gyre. In comparison, the typical electrical output of a nuclear power plant is typically one gigawatt. Discussions about human influence on the Gulf Stream circulation generally involve this overturning circulation.

The heavy deep-sea water masses have to mix with the overlying water masses in another location to complete the overturning circulation. This requires a further driver: tides and winds provide the required energy. This vertical mixing ensures that the circulation of the ocean can persist in the long term, without eventually slackening. Changes in the overturning circulation over periods ranging from decades to a few centuries – these are the time periods that primarily interest us in anthropogenic (man-made) climate change – are mainly due to changes in deep-water formation at the high northern latitudes.

3. Role in the Earth System

The climate has been in a warm period – the Holocene – for approximately the last 11,000 years. Throughout this time, the overturning circulation has been fairly constant. But has this always been the case? Reconstructions of climate change (see Box, p. 10) suggest strong variability and even short-term near-collapses of the overturning circulation. Figure 3 demonstrates the temperature trends of Greenland and the subtropical Atlantic in the last 60,000 years. Sequences of spontaneous cooling (Heinrich events) and abrupt warming (Dansgaard–Oeschger events) can be seen. The last massive slowdown in the current system and the accompanying relatively rapid cooling took place approximately 13,000 years ago and is known as the Younger Dryas (YD) event.

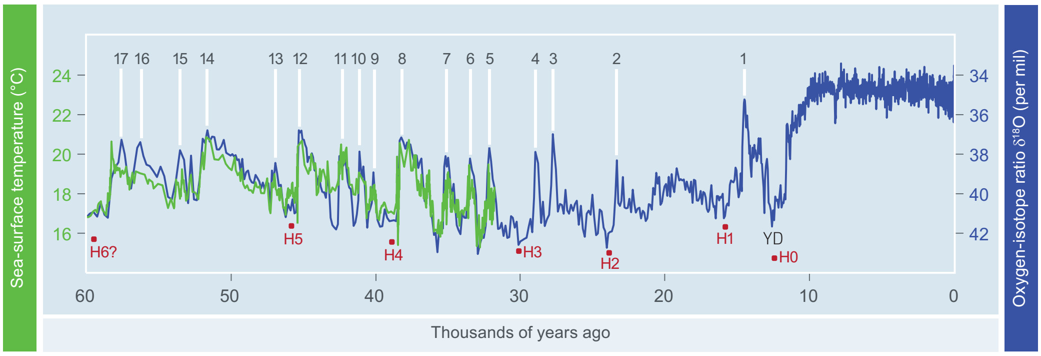


Figure 3: The oxygen-isotope ratio ($\delta^{18}O$) in Greenland ice (blue curve) as an indicator for local temperature, and the reconstruction of sea-surface temperature in the subtropical Atlantic with marine sediments (green curve) over the last 60,000 years. Red points indicate the cooling phases as a result of massive ice surges known as Heinrich events (H). In addition, a series of abrupt warming events known as Dansgaard–Oeschger events (DO) can be seen and are marked with numbers. These are attributed to abrupt changes in Atlantic currents. The high congruity of the blue and the green curves, which are based on different methods and independent data sets, proves that the findings are reliable and that these climate changes were wide-ranging.

The Younger Dryas event occurred at a time when the earth was gradually entering the current warm period, the Holocene, after the last ice age. The sudden decline in the overturning circulation caused the spontaneous cooling of the Northern Hemisphere by several degrees on average. Only then was the Holocene established, characterized by the remarkable stability of its climate (Figure 3). This stability is probably an important factor that has favored the development of human civilization. Man-made climate change could put an end to this stability.

Box: How do I obtain information about the Gulf stream circulation from proxy data?

One of the goals of paleoceanography is to reconstruct ocean currents of the past. Rates and the magnitude of natural climate variability can be determined from proxy data. The ocean floor is the most important "archive" to reconstruct past changes in ocean circulation. The sea floor records a wealth of information about past ocean conditions, which can be investigated using the latest analytical techniques such as mass spectrometry. "Proxies" are geochemical, isotopic, or micropaleontological variables that can be measured directly on bulk sediments or on specific sedimentary components. They allow by means empirical relationships the quantification of oceanic parameters including temperature, salinity, nutrient concentrations, and deep water ventilation rates for times in earth's history.

The temporal and spatial variability of the upper (warm) branch of the Gulf Stream system can be determined from the occurrence of skeletal remains of planktonic microorganisms, geochemical temperature proxies, and their combination with oxygen isotopes. Carbon isotope ratios of microfossil shells reflect the changes in the ventilation of the deep Atlantic caused by the sinking oxygen-rich surface water masses at the northern latitudes. The deep reverse current of cold water can also be determined by its eroding effect on sediments in the area of the Greenland-Faroe Ridge.

Several millennia-long slowdowns in the overturning circulation during extremely cold periods have been documented through the joint analysis of neodymium isotope signals ($^{143}Nd/^{144}Nd$), indicating the origin of water masses, and particulate protactinium/thorium isotope signals ($^{231}Pa/^{230}Th$) from deep sea sediments (Figure 4), among others. Simultaneously, there was a significant reduction in northward heat transport, with a "heat accumulation" in the South Atlantic determined by temperature proxies.

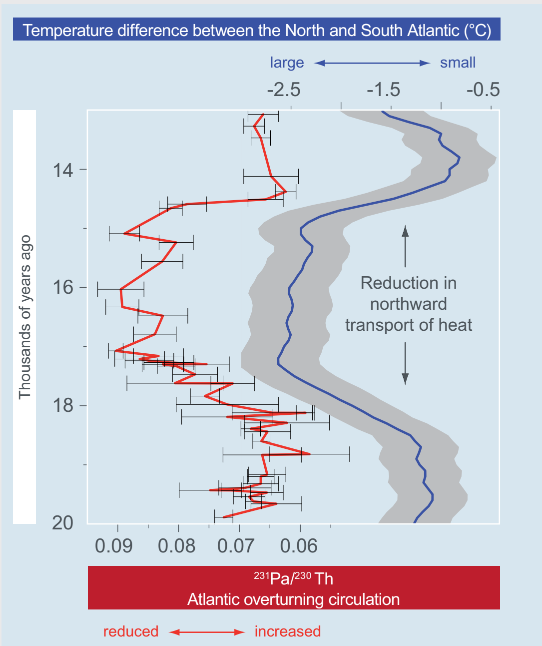


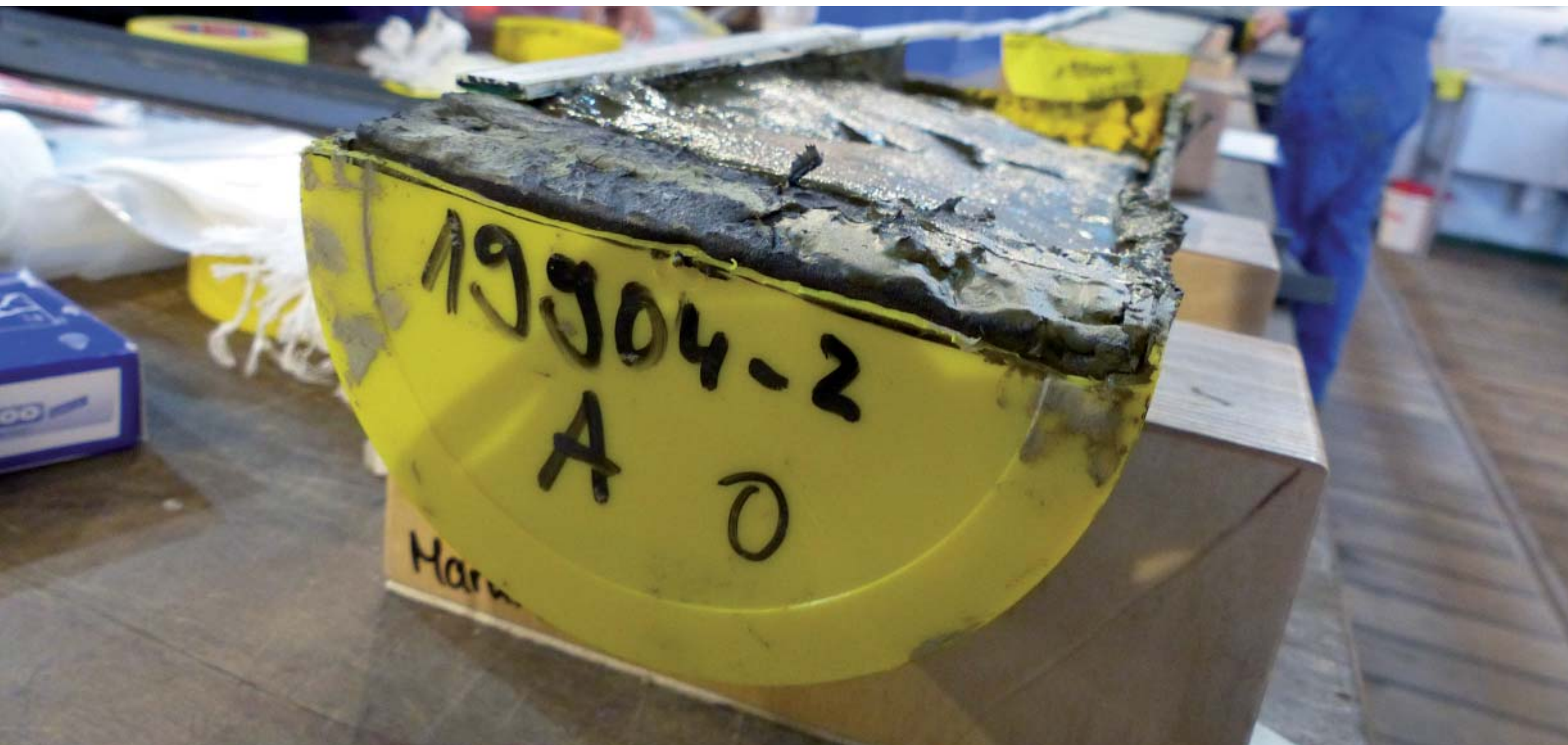
Figure 4: The substantial slowdown of the Atlantic overturning circulation at the end of the last ice age approximately 19,000 years ago, and its subsequent resumption, can be investigated with proxy data. Synchronous changes in the temperature difference between the North and South Atlantic documents the relationship between the strength of the Atlantic overturning circulation and the magnitude of the northward heat transport.

In this context, the trigger for the slowdown in the overturning circulation cannot be ignored – global warming. In many areas of the Northern Hemisphere, the global warming trend would only be slightly weakened by the cooling caused by the weaker overturning circulation.
Thus, ice-age scenarios are complete nonsense.

However, a weakened overturning circulation could have a series of other, not-so-obvious effects:

- Changes in Atlantic hurricane activity, in precipitation in the Sahel zone, or in the Indian summer monsoon are all possible.
- Also, less CO_2 would be transported from the atmosphere into the deeper ocean layers, which would result in more CO_2 in the air, further promoting global warming.
- In addition, a weaker overturning circulation would cause sea level in the North Atlantic to rise and that in the South Atlantic to fall.
- These regional changes would be superimposed on global sea-level rise, with the consequence that the sea-level rise around the North Atlantic would be larger than the global average.

It is for these reasons that a slowdown in the overturning circulation would involve high risks to society.



4. Changes since the beginning of the 20th century

Can we already establish whether the overturning circulation has already slowed due to global warming? In the following, we list essential results derived from observations and climate models.

Developments since the beginning of industrialization involve a superposition of natural and anthropogenic factors. A study that found that the overturning circulation had slowed by around 30% between 1957 and 2004 made the headlines in 2005. This result was based on shipboard measurements across the Atlantic in five different years within this time period. However, five points in time are not sufficient to reliably determine long-term trends.

In addition, the measurement campaigns were held at different seasons. Once seasonal fluctuations were removed, the original 30 percent slowdown was reduced to about 10 percent, i.e. the range of the naturally occurring fluctuations. This and other similar studies show that the existing data is still insufficient to answer our question. The overturning circulation has only been documented directly with measurements since 1995; therefore, this is too short to estimate long-term trends of the last 100 years.

In view of this fact, attempts are being made to indirectly determine changes in the overturning circulation. Since the current system functions like a "central heating unit" and transports huge amounts of heat from the South Atlantic to the North Atlantic, ocean-surface temperatures – which have been documented extensively in the last 100 years – could be used for this purpose. Climate models have given us a sort of fingerprint of when the overturning circulation slows.

This comprises cooling south of Greenland and Iceland, and warming in the South Atlantic (Figure 5). Using this fingerprint, the overturning circulation could actually be in a downward trend. While almost the whole earth has warmed by approximately 1°C on average since 1900, we can find a "warming hole" in parts of the North Atlantic – right where lower temperatures due to a weaker overturning circulation would be expected. Actually, the lowest surface temperatures in this maritime region since the start of extensive instrument measurements were observed in 2015.

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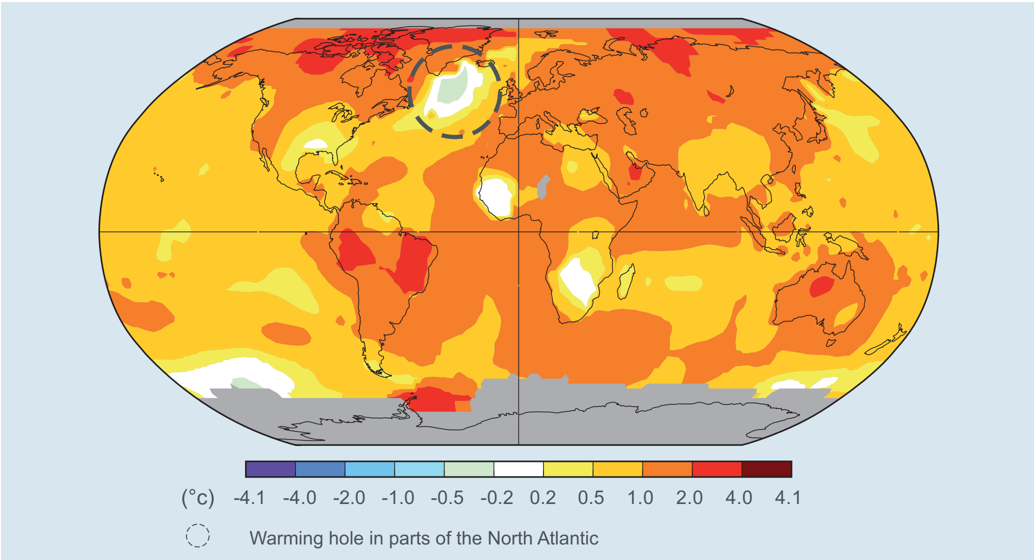


Figure 5: The linear trends of annual sea-surface and air temperatures (°C) measured 2 meters above the ground between 1900 and 2016. The globally averaged temperature trend is about 1°C. The "warming hole" in the North Atlantic is particularly conspicuous because temperatures did not increase or even slightly decreased. Regions with insufficient data are gray.

A number of climate models support this warming hole theory using the atmospheric greenhouse gas concentrations that have been recorded since 1880; however, other models do not.

An alternative theory traces the warming hole back to anthropogenic aerosol emissions, which mainly originate from the combustion of coal and are blown from North America across the North Atlantic by the prevailing westerly winds. There they hinder solar radiation and alter the optical properties of the clouds. Both produce a cooling effect. This shows the difficulty in determining the overturning circulation solely from ocean-surface temperatures, since these changes can have several causes.

Let us take a look at the changes at various depths in the Labrador Sea, a region where deep-water formation occurs and which is of great importance for the overturning circulation.

Quite long data series are available for this region, where measurements began in the 1940s. We know that a stronger overturning is linked to more intense deep water formation and thus to colder temperatures, while a weaker overturning would be visible in warmer temperatures of the deep water. Thus, we would expect a visible warming trend over this long time. Instead, we see a distinct variability (Figure 6). No single year is the same as another; no single decade is the same as another. No long-term trend can be determined from the temperatures, especially at depths of 1,000 meters and below. The Labrador Sea measurements provide no indication that the overturning circulation has been in a decades-long slowdown phase. This result is supported by realistic ocean models forced by observed atmospheric conditions; these also do not produce a long-term trend since the 1940s.

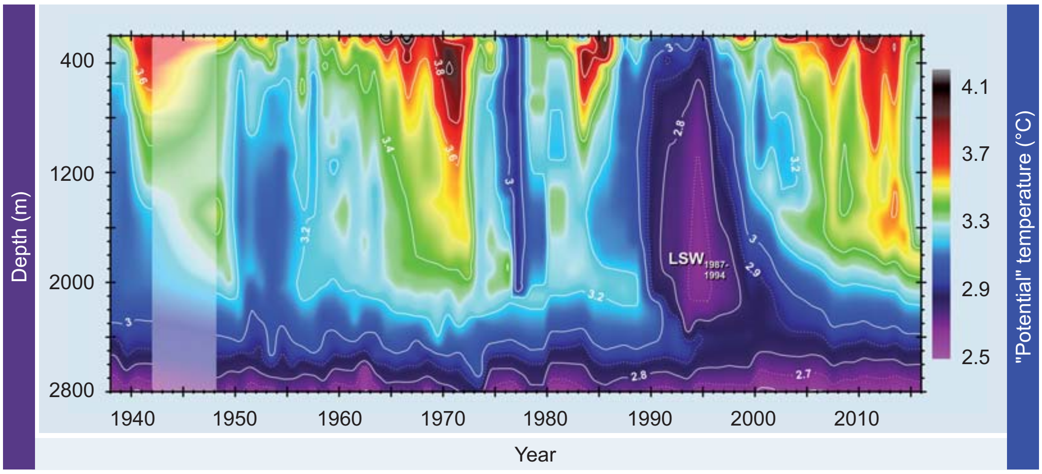


Figure 6: Recorded "potential" temperatures (°C) in the Labrador Sea at different depths since the 1940s. The "potential" temperature serves to make the water temperatures at different depths comparable, by removing the effect of the different pressure. There is very little data available for the time between 1942 and 1948, which is shaded in the graph, making the actual change in temperature uncertain. The water marked LSW from 1987 to 1994 is the coldest deep water formed in the Labrador Sea since measurements began. No long-term trend can be determined from this time series. Had there been a long-term trend, the "potential" temperature lines would be approximately diagonal.

5. The latest developments

The documentation of the high variability of ocean currents from month to month, year to year, and even decade to decade has been a major step forward in marine research during the last two decades. The new data revised the old paradigm of a largely static ocean circulation. We know now that chaotic weather patterns influence deep-water formation and can lead to long-term changes in the overturning circulation. The existence of such natural fluctuations makes it more difficult to detect human influence on the ocean circulation.

The documentation of the high variability of ocean currents from month to month, year to year, and even decade to decade has been a major step forward in marine research.

Since the 1990s, technological and scientific developments have made it possible to directly measure the strength of the overturning circulation at a few key locations using anchored measuring instruments (Figure 7). These current measurements indicate a fairly stable overturning circulation during the last 20 years, even though it is superimposed by unusually high fluctuation. The transport of cold deep water in the Labrador Sea (Figure 7, Graph c) does show a trend that would indicate a slowing of the overturning circulation since 2011. Changes remain within the natural fluctuation range, as demonstrated by the temperature measurements in the Labrador Sea (Figure 6).

Current measurements indicate a fairly stable overturning circulation in the last 20 years.

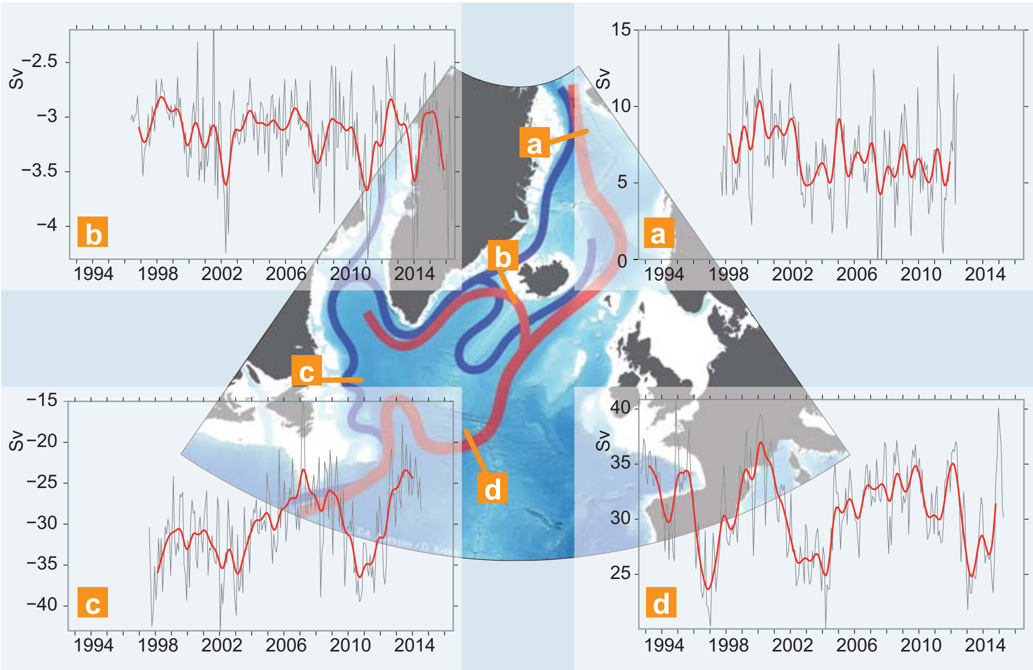
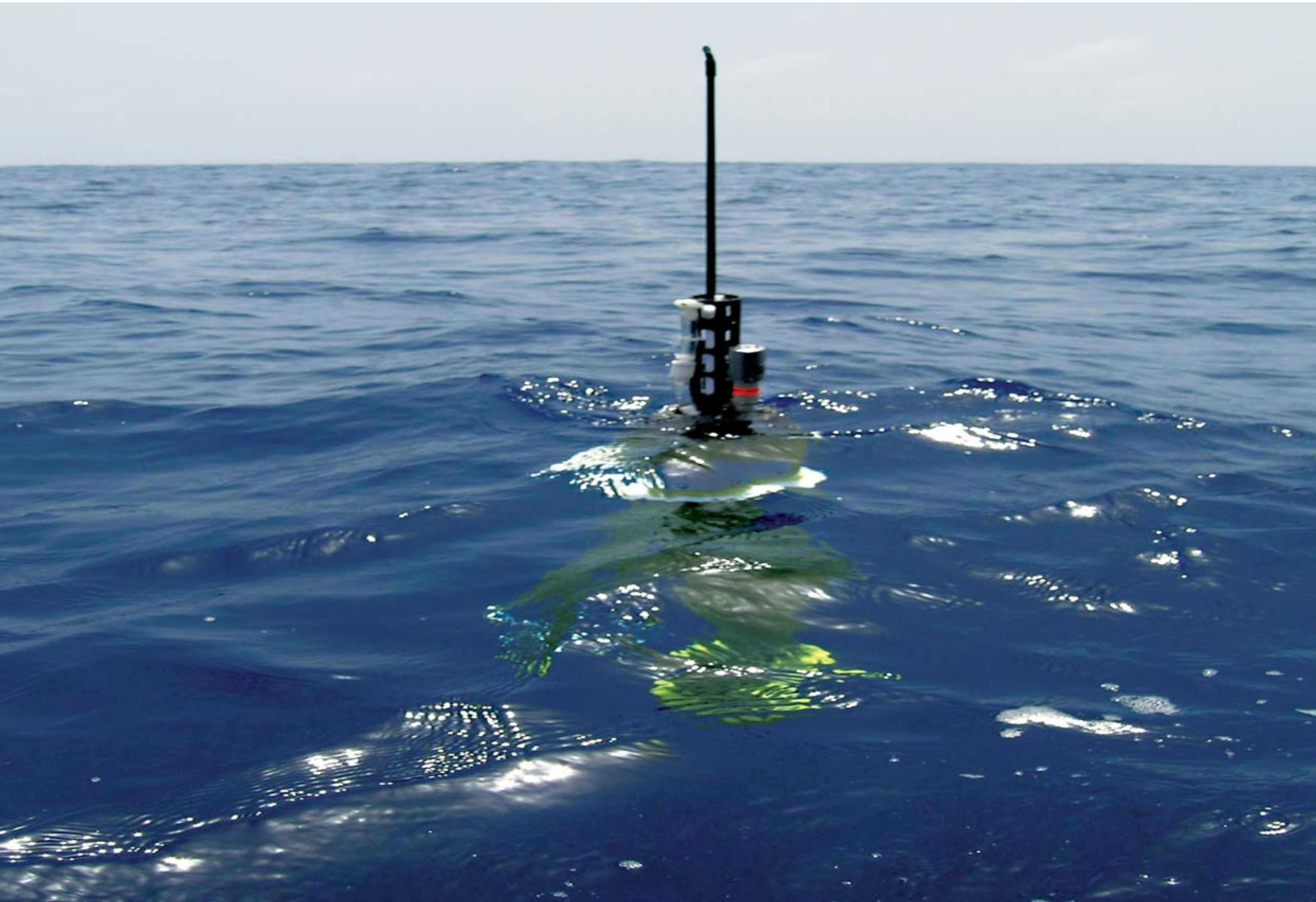


Figure 7: Four transport time series (Sv) of key components of the overturning circulation: a) the transport of warm, salty Atlantic water through Fram Strait into the Arctic Ocean; b) the transport of cold, dense water from the Norwegian-Greenland Sea across the ridge between Greenland and Iceland; c) the transport of cold deep water from the Labrador Sea southward; d) the transport of warm, salty Gulf Stream water and cold deep water from the West to the East Atlantic.

Satellite-based sea-surface height measurements and data from almost 4,000 autonomous profiling drifting buoys in the oceans – providing extensive information on the changes of temperature and salinity distributions at various depths in the upper two kilometers of the ocean as part of the international ARGO program – have also been used to estimate the strength of the overturning circulation. These measuring systems likewise indicate a fairly stable overturning circulation over the last 20 to 30 years.



6. Future scenarios

Climate models can compute the future of the overturning circulation subject to the scenarios for the future development of the atmospheric composition, particularly the CO_2 content of the air. We do not know the path that humankind will pursue and, hence, how the composition of the air will change in the future. This is why such computations are called projections and not predictions: they are if-then statements that represent conceivable "futures". The models also require knowledge about the state of the oceans in the last decades, including that of the deeper ocean layers, to determine the natural variability – which superimposes the anthropogenic change – as accurately as possible. As previously mentioned, these measurements are insufficient. Profiling drifting buoys (ARGO floats) have been providing data from the upper two kilometers of virtually all maritime regions only since 2000.

For this reason, and also due to the still considerable deficits in climate models, such as in the mixing of water masses (for which there are hardly any measurements), there is a wide range in the projections for the overturning circulation until the end of the century (Figure 8). Two greenhouse gas scenarios are considered here: a moderate scenario (RCP4.5) in which emissions peak in 2040, and a worst-case scenario (RCP8.5) in which emissions continue to increase throughout the 21st century.

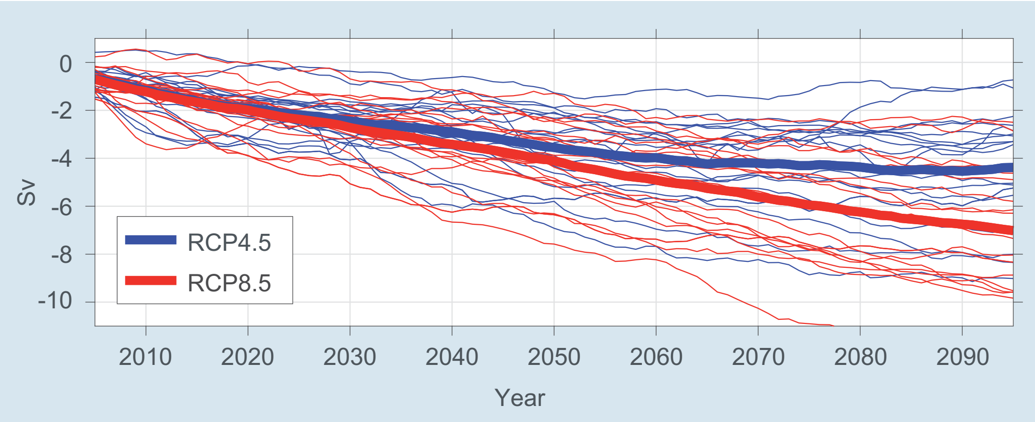


Figure 8: Changes in the overturning circulation (Sv) at 30° N for the 21st century relative to 1970-2000, as projected by different climate models and smoothed using a 10-year filter. These results have been incorporated into the Fifth Assessment Report of the IPCC. Two greenhouse gas scenarios are illustrated: a moderate scenario (RCP4.5, blue lines) and a worst-case scenario (RCP8.5, red lines). The RCP8.5 scenario is consistent with a CO_2 concentration equivalent to 1,370 ppm (parts per million) towards the end of the 21st century, compared to the 650 ppm in the RCP4.5 scenario. The bold lines show the average values of all models. The strength of the overturning circulation at 26.5° N from 1970 to 2000 is 19 Sv on average for all models. The measured strength at 26.5° N from April 2004 to October 2015 was 16.9 ± 4.4 Sv.

The overturning circulation decreases by approximately 30% on average for all models when using the worst-case scenario.

The overturning circulation decreases by approximately 30% on average for all models when using the worst-case scenario (RCP8.5), which almost quadruples the preindustrial CO_2 level in the atmosphere at the end of the 21st century. The overall wide scatter of the results is primarily due to differences between the models rather than differences between the greenhouse gas scenarios, even though the two greenhouse gas scenarios differ considerably. In contrast, in the case of projections for the earth's globally averaged surface temperature, the differences between the greenhouse gas scenarios contribute mostly to the scattering of the results at the end of the 21st century. Longer series of ocean measurements will enable both improvement of the models and more accurate determination of the natural variability to considerably decrease the uncertainty in overturning circulation projections in the future.

How will the Greenland ice sheet respond in the future? This factor is the big unknown in the simulations.

But there are even more factors that make the projections for the coming decades difficult. How will the Greenland ice sheet respond in the future? The simulations do not take the freshwater influx due to the melting Greenland ice into account. This factor, the big unknown, cannot be predicted with high accuracy. The fact of the matter is that the Greenland ice sheet is already losing mass at an average rate of approximately 270 billion tons a year since the start of the satellite measurements. Hence, an even greater slowdown in the overturning circulation is to be expected – by more than 50% of that in some of the previous computations that do not take the influx of meltwater into account. Greenland's ice could melt even faster in the coming decades, which would slow the overturning circulation even more. However, the influence of Greenland meltwater on the overturning circulation depends on whether it reaches the regions of deep-water formation or is steered around them. This is another major research issue to be addressed in the coming years.

7. Conclusion

The overturning circulation has been fairly stable over the past 20 years and the observed fluctuations have remained within the range of natural variability. In order to be able to observe trends that indicate anthropogenic climate change, we need reliable direct measurements over long periods of time, embedded within a dense monitoring network. Although the data gathered has continuously improved since the implementation of drifting buoys (ARGO floats) in 2000 and of the well-placed current profilers since 1995, the time span is not yet sufficient to come to definitive conclusions.

However, based on the currently available data as well as our knowledge of the physics of the oceans and the climate system, we expect a significant slowdown by the end of the 21st century. The actual dimension of this slowdown is still uncertain and will very much depend on the big unknown, namely the fate of Greenland's ice.

The observation of the entire ocean and long series of measurements are complex and expensive. Furthermore, selective and ad hoc measurements do not allow us to draw clear conclusions. Much further research, improved models, and more comprehensive data series are thus necessary for reliable projections. For that purpose, high-technology instrumentation is required that can be used on research vessels, satellites, or even autonomous or remote-controlled devices. Efficient data management and mainframe computers are further prerequisites to more quickly, better, and more accurately understand the processes that control the Gulf Stream circulation and the effects that are relevant for life and societies in northern and western Europe.

Although the abrupt cooling in Europe in response to a sudden collapse of the overturning circulation is anxiously debated by the public, scientists consider this scenario to be extremely unlikely. Nonetheless, researchers are seriously worried about the allegedly certain slowdown and the associated risks. These include positive feedbacks, which further aggravate global warming, cause long-term and irreversible shifts in precipitation patterns, or provide additional impetus for the already dangerous sea-level rise, especially in the northern mid-latitudes.

A significant slowdown in the circulation would definitely have considerable aftereffects on the climate, sea level, the carbon cycle, and marine ecosystems.

It would also have serious socioeconomic effects. The expected global sea-level rise of around 30 to 80 cm by the end of the century, projected in the Fifth Assessment Report of the IPCC, would be even higher in Europe at times of a weakened overturning circulation. Ecosystems and human society would come under pressure because the Gulf Stream circulation shapes the floral and faunal communities, as well as the history and culture, of the European countries.

The prevailing mild temperatures and sufficient precipitation give rise to green landscapes with high biodiversity and reliably high agricultural crops. The high yields of Atlantic fisheries are also related to the Gulf Stream circulation, because both temperatures and currents effectively shape the distribution of nutrients and food.

Due to the related mild climate in northwestern and northern Europe, the overturning circulation is not only of outstanding societal significance: due to its central role in the global deep circulation of the oceans, it even reaches into the other ocean basins and could, in the long term, impair the supply of oxygen in the deep sea.

Unabated climate change will contribute to terminating a relatively stable climate that has lasted more than 10,000 years; humankind will likely have to cope with changes that are unprecedented in history, culture, or tradition. We cannot predict exactly how the overturning circulation will change. The consensus among scientists, however, is that it will slow down in the coming decades. Whether this will occur abruptly or gradually remains an open question. In any case, the consequences would be far-reaching.

Glossary

Aerosols: Suspended solid or liquid particles in the atmosphere.

ARGO floats: Autonomous profiling drifting buoys that are able to sink and rise in the water column, measuring temperature, conductivity, and pressure between the surface and a 2,000-meter depth, and transmitting this data to satellites. Two important physical variables that describe the current system can then be determined from the data: salinity and density. More than 30 nations constantly use almost 4,000 drifting buoys in all the oceans within the scope of the ARGO program.

Atlantic circulation: The Atlantic component of the global overturning circulation, also: the Atlantic component of the "global ocean conveyor belt".

Density of seawater: In oceanography, extremely accurate measurements of salinity and temperature are used to determine the potential density of seawater to distinguish the currents based on the horizontal differences in density. The potential density is the density that the water would acquire if brought to the surface from its original depth.

Gulf Stream: This is actually only the section along the eastern coast of North America; its use as a synonym for Gulf Stream circulation or even Atlantic circulation is a popular misconception.

Gulf Stream circulation: The current in the upper, warm ocean layers of the Atlantic circulation stretching from the Florida Strait through the North Atlantic to the Arctic.

Overturning circulation or thermohaline circulation (synonyms): Ocean circulation driven primarily by horizontal differences in the density of seawater. These differences in density are determined mainly by temperature and salinity.

Sverdrup (Sv): Commonly used unit in oceanography for the transport of large volumes of water; named after the Norwegian oceanographer Harald Sverdrup. 1 Sv = 1 million $m^{3/s}$.

Literature

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 p.

Yashayaev, I. & Loder, J.W. (2016). Further intensification of deep convection in the Labrador Sea in 2016. Geophys. Res. Lett., doi:10.1002/2016GL071668.

Figures and photos

Further reading

Archer, D. & Rahmstorf, S. (2010). The Climate Crisis. Cambridge University Press.

Deutsches Klima-Konsortium DKK (ed.) (2015). Future Prospects for Climate Research 2015 to 2025. Position paper. Berlin.

Federal Ministry of Education and Research (BMBF), Unit System Earth (ed.) (2012). Climate research in the ocean: Changing ocean currents and future climate. Bonn.

Heinrich Boell Foundation Schleswig-Holstein, the Heinrich Boell Foundation (national foundation), and the University of Kiel's Future Ocean Cluster of Excellence (ed.) (2017). Ocean Atlas. Facts and Figures on the Threats to Our Marine Ecosystems. Berlin.

Latif, M. (2008). Climate Change – The Point of No Return. Haus Publishing.

Maribus, in cooperation with the University of Kiel's Future Ocean Cluster of Excellence, International Ocean Institute, Mare (ed.) (2010): World Ocean Review. Living with the oceans. Hamburg.

Rahmstorf, S. & Richardson, K. (2007). Our Threatened Oceans. Haus Publishing.

WBGU (2006). The Future Oceans – Warming Up, Rising High, Turning Sour. Special Report 2006. Berlin.

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About us

DKK and KDM “Ozeanzirkulation und Klima” strategy group

The ocean is one of the central components of the climate system. Changes in the oceans affect the climate in several ways. Therefore, interdisciplinary collaboration in climate and marine research is crucial. The “Ozeanzirkulation und Klima” (Ocean Circulation and Climate) joint strategy group of the Deutsches Klima-Konsortium (DKK) and the Konsortium Deutsche Meeresforschung (KDM) brings together scientists from the major German research organizations involved in this area. It identifies pressing issues related to the role of the oceans in climate change and uses research to develop a knowledge base for political decisions.

Deutsches Klima-Konsortium (DKK)

The Deutsches Klima-Konsortium e. V. (DKK) represents the leading stakeholders in German climate and climate impact research. These include universities, non-university research organizations, and federal agencies. The DKK promotes science-based political consulting, addresses current issues, and provides background information based on expert opinions.

German Marine Research Consortium / Konsortium Deutsche Meeresforschung (KDM)

The Konsortium Deutsche Meeresforschung (KDM – German Marine Research Consortium) integrates expertise in German marine research. Its members comprise all research organizations involved in marine, polar, and coastal research. One of the main objectives of the KDM is to represent the interests of marine research in relation to national decision-makers, the EU, and the general public.

Deutsches Klima Konsortium

Konsortium Deutsche Meeresforschung

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