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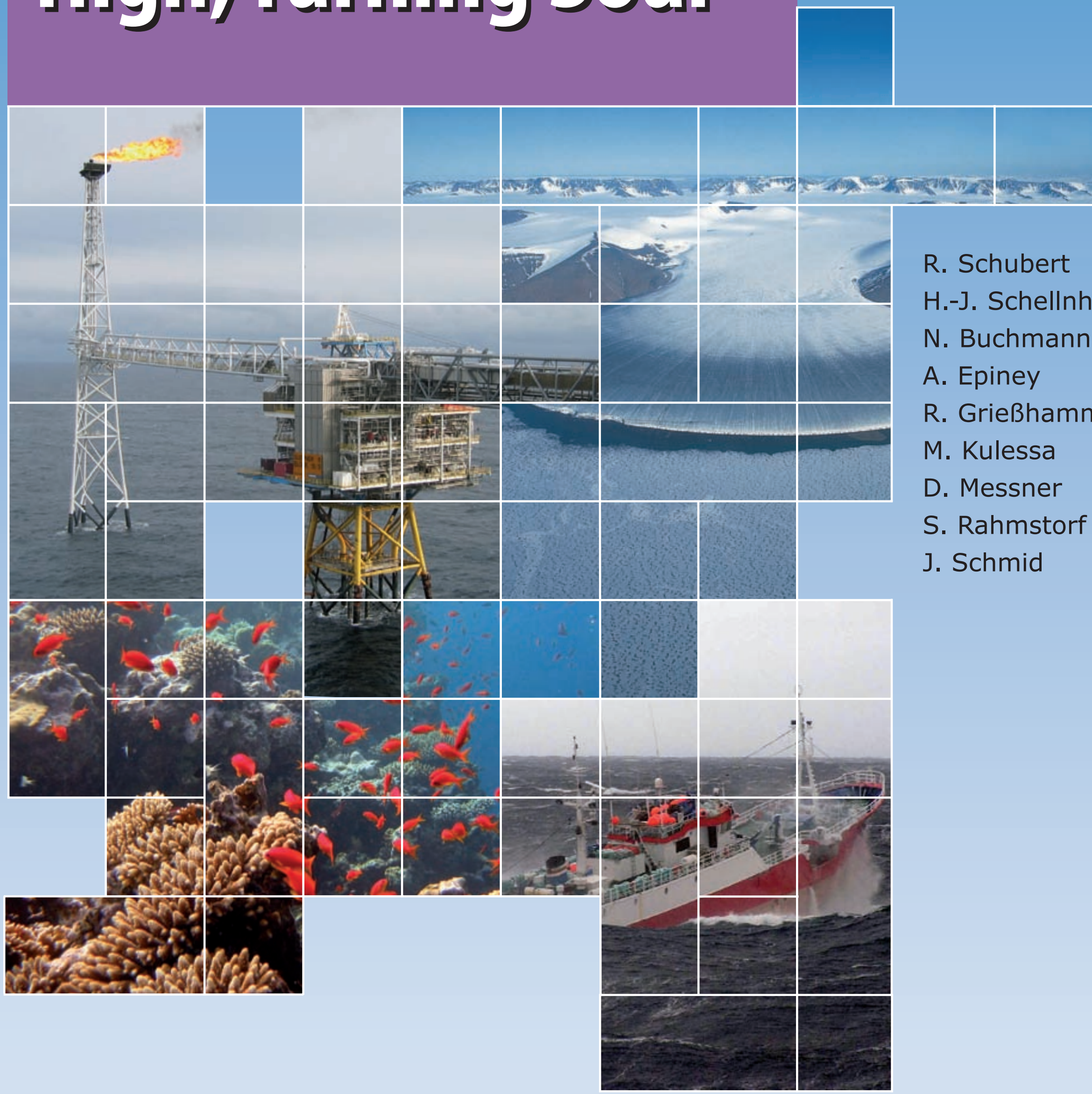
German Advisory Council on Global Change
(WBGU)

The Future Oceans – Warming Up, Rising High, Turning Sour

Special Report



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Summary for policy-makers

The latest research findings show that climate change will subject the marine environment and the coasts to major change and damage that are likely to have severe consequences for humankind. Ocean surface waters are warming, the sea level is rising ever faster, the oceans are becoming increasingly acidic and marine ecosystems are under threat. Human activities are unleashing processes of change in the oceans that are without precedent in the past several million years. Due to the considerable geophysical time lags, these processes will determine the state of the world's oceans for millennia to come. Humanity is thus intervening in a pivotal mechanism of the Earth System, and many of the consequences cannot yet be predicted accurately. Resolute and forward-looking action is needed in order to ensure that the oceans do not overstep critical system boundaries. The way we handle the oceans will be a decisive test of humankind's ability to steer a sustainable course in the future.

Climate mitigation for marine conservation

Ocean warming, ocean acidification and a distinct sea-level rise are all already measurable. The causes are clear: elevated concentrations of greenhouse gases in the atmosphere caused by human activities have led to a global warming that has also increased temperatures in the surface waters of the oceans. This leads to rising sea levels due to thermal expansion of the water and due to melting ice masses. At the same time, the continuously rising carbon dioxide concentration in the air causes CO_2 to be absorbed by the sea where, through chemical reactions, the seawater acidifies. These changes can only be mitigated by means of drastic reductions in anthropogenic greenhouse gas emissions. Rapid action is therefore required:

- Ambitious climate protection measures are needed to limit the consequences of warming, acidification and sea-level rise for the marine environment and human society. WBGU therefore recommends that global anthropogenic greenhouse gas emissions must be approximately halved by 2050 from 1990 levels. Adaptation measures can only succeed if the present acceleration of sea-level rise and the increasing acidification of the oceans are halted.
- The guard rail already recommended previously by WBGU – namely limiting the rise in near-surface air temperature to a maximum of 2°C relative to the pre-industrial value while also limiting the rate of temperature change to a maximum of 0.2°C per decade – is essential not only to prevent dangerous climatic changes but also to maintain the state of the oceans.

Bolstering the resilience of marine ecosystems

Compared to terrestrial ecosystems, marine ecosystems respond much more sensitively and rapidly to climatic changes, for example through spatial shifts of populations. As a result, human-induced warming of the surface waters can cause changes in food webs and species composition that are difficult to predict. A further increase in water temperatures, in combination with continuing acidification, will have major overall impacts on marine ecosystems and also on fisheries.

The fisheries sector is thus facing two further threats in the future in the shape of climate change and ocean acidification, in addition to the consequences of overfishing, which are already drastic enough in themselves. Taken together, and in view of the continuing growth of the world population, these anthropogenic factors will jeopardize a sufficient supply of food from the oceans.

Tropical coral reefs, by far the most species-rich ecosystems in the ocean, are acutely threatened by climate change. Most reefs may be destroyed within the next 30–50 years, because many corals are not viable at higher water temperatures. The local ramifications are vast, reefs being indispensable for coastal protection and in supplying protein for millions of people.

One of the most visible consequences of warming is the retreat of Arctic sea ice. Over the past 30 years, summertime ice cover has declined by 15–20 per cent. Model scenarios for the future indicate that, unless action is taken to mitigate climate change, the Arctic Ocean will be practically ice-free in summertime by the end of the 21st century. This would have severe consequences for ecosystems and climatic processes.

- To preserve marine biodiversity and strengthen the resilience of marine ecosystems, WBGU proposes the following guard rail: at least 20–30 per cent of the area of marine ecosystems should be designated for inclusion in an ecologically representative and effectively managed system of protected areas. There is a particular need to enhance marine conservation significantly for coral reefs and areas that are nursery grounds for fish populations. Goals for marine protected areas already agreed by the international community need to be implemented, and the regulatory gap in this regard for the high seas should be closed by adopting an agreement under the United Nations Convention on the Law of the Sea (UNCLOS).
- Marine resource management should follow the 'ecosystem approach'. In particular, the publicly subsidized overfishing of the oceans must be terminated, not least in order to strengthen the resilience of fish stocks to the impacts of climate change. This necessitates not only removing fisheries subsidies, but also dismantling excess fishing capacity and taking measures to combat destructive fishing practices and illegal or unregulated fisheries.
- Our understanding of the linkages between anthropogenic disturbances, biological diversity and the resilience of marine ecosystems needs to be improved. Intensive monitoring is a precondition for the further development of coupled ecosystem-climate models.

Limiting sea-level rise and reorienting coastal zone management strategies

Climate change causes sea-level to rise, particularly due to ocean warming and the melting of inland glaciers and continental ice sheets. Throughout the 20th century, global sea-level rise averaged 1.5–2.0cm per decade. Satellite measurements show that the decadal rate already reached 3cm in the past decade. If warming continues, there is a risk of further acceleration of sea-level rise. There are indications that the continental ice sheets on Greenland and in the Antarctic are beginning to disintegrate. This has the potential to cause several metres of sea-level rise in the next centuries.

Besides sea-level rise, the increasingly destructive force of hurricanes is a further factor threatening many coastal areas. Theory, observed data and mathematical models agree that while climate warming does not increase the number of hurricanes, it does boost their destructive energy. Tropical sea-surface temperatures have warmed by only half a degree Celsius, while an increase in the energy of hurricanes by 70 per cent has been observed.

Sea-level rise and extreme events such as hurricanes and storm surges are threatening the coasts. Coastal protection is thus becoming a key challenge for society, not least in economic terms. Past strategies for protecting and utilizing coastal areas fail to do justice to this development. Novel combinations of measures (portfolio strategies) are called for, whereby the options of protection, managed retreat and accommodation need to be weighed against each other. In particular, coastal protection and nature conservation concerns must be better linked, and the people affected by adaptation or resettlement measures need to be involved in decision-making on such measures.

- Guard rail: Absolute sea-level rise should not exceed 1m in the long term, and the rate of rise should remain below 5cm per decade at all times. Otherwise there is a high probability that human society and natural ecosystems will suffer unacceptable damage and loss.
- Because of anticipated sea-level rise, national and international strategies need to be developed for protection and accommodation, but also for a managed retreat from endangered areas.
- There is a need to improve the linking of nature conservation with coastal protection. The process of drawing up coastal protection plans and strategies for the sustainable use and development of coastal zones must integrate all key policy spheres (integrated coastal zone management).

Adopting innovative instruments of international law for refugees from sea-level rise

Sea-level rise will lead to the inundation of coasts and small island states and thus to migration of 'sea-level refugees'. Under international law as it stands at present, there is no obligation to receive refugees from coastal areas, nor is the question about costs resolved. In the long term, however, the international community will not be able to ignore the problem of refugees from coastal areas and will therefore need to develop appropriate instruments to ensure that affected people are received in suitable areas, ideally areas corresponding to their preferences.

- There is a need for agreements on the reception of refugees from coastal areas and on the apportionment of the associated costs, e.g. by means of a compensation fund. It would be expedient to develop a fair burden-sharing system, under which states make a binding commitment to assume responsibility for the migrants.
- To inform the policymaking process, studies should be undertaken in the fields of law and social sciences.

Halting ocean acidification in time

The dissolution of carbon dioxide in seawater leads to considerable acidification (decrease in pH) and thus to changes to the biogeochemical carbonate balance. The oceans have absorbed about one-third of all anthropogenic CO_2 emissions to date, which has already caused a significant acidification of seawater. Such emissions thus influence the marine environment directly – in addition to the route via climate change. Unabated continuation of this trend will lead to a level of ocean acidification that is without precedent in the past several million years and will be irreversible for millennia. The effects upon marine ecosystems cannot yet be forecast exactly but there is a risk of profound changes to the food web, as calcification of marine organisms may be impeded or in some cases even prevented. We are now seeing on a global scale problems similar to those that arose regionally when lakes acidified in the 1970s and 1980s ('acid rain').

- In order to prevent disruption of the calcification of marine organisms and the resultant risk of fundamentally altering marine food webs, the following guard rail should be obeyed: the pH of near surface waters should not drop more than 0.2 units below the pre-industrial average value in any larger ocean region (nor in the global mean).
- Engineering approaches to mitigate acidification, such as large-scale liming, are not feasible in the oceans. It is therefore important to ensure that anthropogenic CO_2 emissions are limited, regardless of reductions of other greenhouse gas emissions. WBGU thus recommends taking the special role of CO_2 compared to other greenhouse gases into account in the negotiations on future commitments under the United Nations Framework Convention on Climate Change. The consequences of acidification for marine ecosystems and for biogeochemical cycles are still insufficiently understood. Considerable further research is needed in this regard.

Regulating CO_2 storage

Engineering approaches can be used to capture the carbon dioxide arising from the utilization of fossil energy sources, and to compress it and transport it via pipelines or by ship to permanent repositories. CO_2 can be stored in geological formations on land or under the sea floor. Theoretically, the CO_2 could also be injected into the deep sea. Such approaches, however, involve a risk of continuous, slow release of the stored CO_2 into the atmosphere, which runs counter to long-term climate mitigation. The specific benefits and drawbacks of the technical and economic development of sequestration technologies therefore need to be balanced against other climate mitigation approaches such as improving energy efficiency or switching to renewable energy sources.

- The precautionary principle indicates that introducing CO_2 into seawater should be prohibited, because the risk of ecological damage cannot be assessed and the retention period in the oceans is too short.
- Storing CO_2 in geological formations under the sea floor can only be an 'emergency' solution for a transitional period. Permits for such measures should only be granted if they meet strict criteria with regard to technical safety and, above all, with regard to the permanence of storage and its low environmental impact. These criteria should also apply to the use of CO_2 for 'Enhanced Oil Recovery'. CO_2 sequestration must not lead to neglect of sustainable emissions reduction strategies (such as efficiency improvement and the promotion of renewable energies) and should therefore not be supported with public funds.
- Only a proportion of the CO_2 stored under the sea floor should be eligible as prevented emissions when drawing up emissions inventories and for the purposes of the flexible mechanisms in international climate policy. This is necessary in order to take the risk of leakage into account. Specific liability rules also need to be established.

Imposing strict conditions upon methane hydrate mining

Quantities of carbon are stored in the sea floor in the form of methane hydrates that are of the order of magnitude of total worldwide coal reserves. Methane hydrates are only stable under high pressure and at low temperature. Such conditions typically prevail on the sea floor from depths of around 500m downwards; in the Arctic this boundary is somewhat higher. The stability of methane hydrate stocks can be compromised by climate change, by disturbances resulting from mineral oil and natural gas production, or, in the future, possibly by direct mining of the hydrates themselves. WBGU takes the view that the hazard of a sudden release of larger, climate-relevant quantities of methane within this century is very small. Over the long term, however, the slow penetration of global warming to lower ocean layers and sediments could cause gradual methane releases over many centuries to millennia.

- Because of the potential instabilities of deposits, it is important to ensure even now that methane hydrate mining in the oceans is only permitted under very strict conditions. Existing regulatory systems governing ocean mining should be amended and adjusted accordingly.

Complementing the existing financing mechanisms

Measures to mitigate and cope with the anticipated adverse effects of climate change upon the marine habitat can be funded from existing international funds whose task is to finance emissions reductions or adaptation projects. It must be expected, however, that these resources will not suffice for the tasks outlined in the present report, above all because they do not budget for specifically ocean-related projects. To complement these resources, WBGU therefore recommends:

- Fisheries subsidies must be removed in order to avoid providing misplaced incentives for overfishing. The public funds thus released could then be invested partly in marine conservation.
- Charges should be levied on the use of the oceans by shipping, and the revenues earmarked.
- The establishment of microinsurance systems to protect individual assets should be supported as a component of a more comprehensive precautionary strategy, e.g. through public co-financing, especially in developing countries.
- Some of the official development assistance (ODA) resources presently deployed to provide emergency relief worldwide should be diverted into preventive measures.

With this special report, WBGU has taken up an issue that until now has attracted little attention, and whose profound implications are largely underestimated. The state of the marine environment is of elementary importance to the future of the blue planet Earth. Through overexploitation and pollution, humankind has already inflicted great damage on the oceans. Global climate change is presenting a further, completely new dimension of threat. The present report pinpoints the threats and identifies required actions and options that arise at the interface of climate change and the oceans. The report hopes to encourage policy-makers to tackle the necessary measures in time and with resolve, to prevent the oceans from becoming too warm, rising too high and turning too sour.

1 Introduction

The oceans are changing rapidly. Surface waters are warming, sea-level rise is accelerating and the oceans are becoming increasingly acidic, jeopardizing many marine ecosystems. Human activities are unleashing processes of change in the oceans that are without precedent in the past several million years. Humanity is thus interfering with pivotal mechanisms of the Earth System. The oceans play a key role in the carbon cycle of our planet and have absorbed about one-third of total anthropogenic CO_2 emissions until now. Covering more than two-thirds of the Earth's surface, the oceans initially take up the greater part of incoming solar heat and thus determine our climate system. Similarly, the global water cycle is driven mainly by evaporation from the oceans. Finally, the oceans harbour a great wealth of biological diversity and, through fisheries, supply humankind with vital proteins. An intact marine environment is also an important factor for economic development, social well-being and human quality of life.

Recent research is making it increasingly clear that climate change will change and damage the marine environment and the coasts. These effects will also impact severely upon human society. A large and growing part of the population now lives close to coasts. The threats posed to coastal populations and infrastructure by rising sea levels and extreme events such as storm surges or hurricanes will mount in coming decades. Furthermore, together with drastic overfishing, climate change and acidification can endanger food supply from the oceans. There is an urgent need for action now in order to limit the adverse effects of climate change upon ecosystems and human society, especially because, due to the considerable time lags, the present behaviour of humankind will determine the state of the world's oceans for millennia to come. A strong research effort is also needed, for the oceans are still terra incognita in many respects.

One important reason to produce this special report is the changed scientific understanding of sea-level rise and ocean acidification since the Intergovernmental Panel on Climate Change published its last assessment report (IPCC, 2001). Furthermore, recent events such as the unusual hurricane season of 2005, or the ongoing debate on methane hydrates and carbon storage, present a need for WBGU, the German Advisory Council on Global Change, to state its views. By analysing the climatic impacts upon the oceans, WBGU draws attention to the need for and urgency of efforts to engage in vigorous climate mitigation activities and develop appropriate adaptation strategies. WBGU also wishes to contribute its findings to the process of shaping a new European Union policy on seas and oceans.

This special report does not seek to paint a comprehensive picture of the state of the oceans. It does not, for instance, set out to recapitulate the many years of debate on ocean overfishing. WBGU concentrates instead on those key linkages between climate change and the oceans that are the topic of new scientific insights. These insights include new findings on warming, ocean currents, sea-level rise, carbon uptake and acidification, and on the impacts of these factors upon marine ecosystems. The report also discusses in detail the development of tropical cyclones, the issues surrounding carbon storage in the ocean or under the seabed, and the risks associated with methane hydrate deposits in the sea floor. Many of these issues are closely interlinked – coral reefs, for instance, are affected simultaneously by warming, sea-level rise, storms and acidification. Each theme is explored systematically, starting with the physical and chemical fundamentals, proceeding to the ecological impacts, moving on to the consequences for human society, and finally deriving policy and research recommendations on that basis. WBGU embeds its analysis within a normative framework that it has developed – the 'guard rail' approach (Box 1-1). Analogous to the 'climate guard rail' that it developed previously, WBGU now proposes a set of 'ocean guard rails' for the sustainable management of the oceans. These are quantitative boundaries that must not be overstepped.

Resolute and forward-looking action is needed to ensure that the oceans do not cross critical system boundaries within a matter of decades. Overstepping these boundaries would lead to severe and partly

Box 1-1

The guard rail concept

WBGU has developed the idea of guard rails to operationalize the concept of sustainable development (e.g. WBGU, 2004). Guard rails are limits on damage and can be defined quantitatively; a breach of these limits would give rise either immediately or in future to intolerable consequences so significant that even major utility gains in other fields could not compensate for the damage. Guard rails thus demarcate the realm of desirable and sustainable development trajectories. For instance, WBGU has argued repeatedly in previous reports that the average mean temperature should not be allowed to rise more than 2°C above the pre-industrial level. Beyond that value, a domain of climate change begins that is characterized by non-tolerable developments and risks.

The guard rail approach proceeds from the realization that it is scarcely possible to define a desirable and sustainable future in positive terms, in other words as a specific target or state that should be achieved. It is, however, possible to agree on the demarcation of a domain that is recognized as unacceptable and which society wishes to prevent. Within the guard rails, there are no further requirements at first. Society can develop in the free interplay of forces. Only if a system is on course for collision with a guard rail must measures be taken to prevent it crossing the rail. Compliance with all guard rails does not mean, however, that all socio-economic abuses and ecological damage will be prevented, as global guard rails cannot take account of all regional and sectoral impacts of global change. Moreover, knowledge is limited and misjudgement is possible. Compliance with guard rails is therefore a necessary criterion for sustainability, but it is not a sufficient one.

The analogy of road traffic may serve to illustrate the guard rail concept. Guard rails have a function similar to that of speed limits, e.g. a limit permitting a maximum of 50km per hour in built-up areas. The outcome of setting the limit at 40, 50 or 60km per hour can be determined empirically, but in the final analysis the choice of figure is a normative decision, representing an expedient way to handle a risk collectively. Compliance with the speed limit cannot guarantee that no serious accidents will occur, but it can keep the risk within boundaries accepted by society. The guard rails formulated by WBGU build upon fundamental norms and principles agreed by the international community in various forms. They can be no more than proposals, however, for the task of defining non-tolerable impacts cannot be left to science alone. Instead, it should be performed – with the support of scientists – as part of a worldwide, democratic decision-making process. For instance, compliance with the climate guard rail (no more than 2°C global warming) has now been adopted as a goal by the European Union.

Guard rails for marine conservation

In the present report, WBGU applies its guard rail approach to the field of marine conservation. This builds upon earlier reports, in which WBGU has repeatedly argued for a two-fold climate guard rail (WBGU, 1995, 2003). The environmental changes in the oceans discussed in this report further underpin the need for the climate guard rail. In addition, the report develops further guard rails. Each is concerned with a specific aspect of the interplay between climate change and the oceans, and is elucidated and argued in a separate chapter. The full set of guard rails is as follows:

- *Climate protection:* The mean global rise in near-surface air temperature must be limited to a maximum of 2°C relative to the pre-industrial value while also limiting the rate of temperature change to a maximum of 0.2°C per decade. The impacts of climatic changes that would arise if these limits are exceeded would also be intolerable for reasons of marine conservation.
- *Marine ecosystems:* At least 20–30 per cent of the area of marine ecosystems should be designated for inclusion in an ecologically representative and effectively managed system of protected areas.
- *Sea-level rise:* Absolute sea-level rise should not exceed 1m in the long term, and the rate of rise should remain below 5cm per decade at all times. Otherwise there is a high probability that human society and natural ecosystems would suffer non-tolerable damage and loss.
- *Ocean acidification:* In order to prevent disruption of calcification of marine organisms and the resultant risk of fundamentally altering marine food webs, the following guard rail should be obeyed: the pH of near surface waters should not drop more than 0.2 units below the pre-industrial average value in any larger ocean region (nor in the global mean).

irreversible damage to nature and human society. The way we manage the oceans now will thus be a decisive test of humankind's ability to steer a sustainable course in the future.

Global warming and marine ecosystems 2

2.1 Climatic factors

2.1.1 Rising water temperatures

The temperatures in the ocean influence sealife as well as the solubility of carbon dioxide in the water. They change the density of seawater, thereby influencing the currents and the sea level: the thermal expansion of water contributes considerably to sea-level rise. The sea surface temperature also affects the atmosphere in a multitude of ways. The mild Atlantic air that is often felt in Europe during the winter obtains its heat from the relatively warm ocean. High water temperatures also lead to increased evaporation, which is an important energy source for the atmosphere (for example, in tropical cyclones) and a source of water for many intensive precipitation events (among others, the Elbe river flood of 2002 in Germany).

Significantly improved data sets of global ocean temperatures covering the past 50 years have become available to researchers in recent years through international efforts in the exchange of data (NODC, 2001). Based on over 7 million measured temperature profiles, Levitus et al. (2005) have reconstructed a time series of the heat content of the world ocean. They report an increase in the amount of stored heat of $15 \cdot 10^{22}$ joules from 1955 to 1998. This corresponds to an average heat absorption of 0.2 watts per m^2 for this time period when averaged across the entire surface of the Earth. For the period from 1993 to 2003 heat absorption was even greater, at 0.6 watts per m^2 (Willis et al., 2004). This increase of heat in the ocean indicates that the Earth is presently absorbing more energy from the sun than it can radiate back into space. This reveals a state of disequilibrium in the heat budget of the Earth, as is to be expected due to the anthropogenic greenhouse effect (Hansen et al., 2005).

Averaged globally and throughout the entire water column, the temperature of the ocean has only risen by 0.04ºC since 1955. So far only the surface mixed layer with a thickness of a few hundred metres has warmed, while the average ocean depth is 3800m. The amount of sea-level rise caused by thermal expansion of the water so far is therefore only a small fraction of what will result when the warming extends into the deep sea over the coming centuries (Section 3.1.1).

Figure 2.1-1 shows the variation of the sea-surface temperature, which is very important for the climate system. It shows a strong similarity to the development of air temperatures, but the warming is not as pronounced (0.6°C since the beginning of the twentieth century). These two facts are not surprising. Thermally, the sea surface is closely coupled to the overlying atmosphere. Making up 30 per cent of the Earth's surface, the land masses, because of their lower heat capacity, warm up more quickly than the oceans, so the global mean air temperature rises generally more quickly than that of the ocean. A data set of air temperatures measured by ships at night above the sea surface (Parker et al., 1995) shows a pattern very similar to the water temperatures. These data support the fact of a warming trend in the ocean surface waters and once more confirm the global warming measured by weather stations.

Figure 2.1-2 shows the increase in surface temperatures in the North Atlantic, which in large part range between 0.3 and 1°C over the indicated time period. A significantly stronger warming of several degrees is seen in Arctic latitudes, primarily because of the positive (strengthening) feedback with the shrinking sea ice (Section 2.1.1). Some small areas, however, show a cooling trend due to dynamic changes in the sea. This is particularly true of the Gulf Stream region off the coast of the USA and in regions near Greenland. The reason is probably natural internal fluctuations in the circulation, which superimpose the general warming trend caused by greenhouse gases.

The increase of sea temperatures in tropical latitudes is of particular interest because it influences tropical storms. This will be discussed in Section 3.1.2.

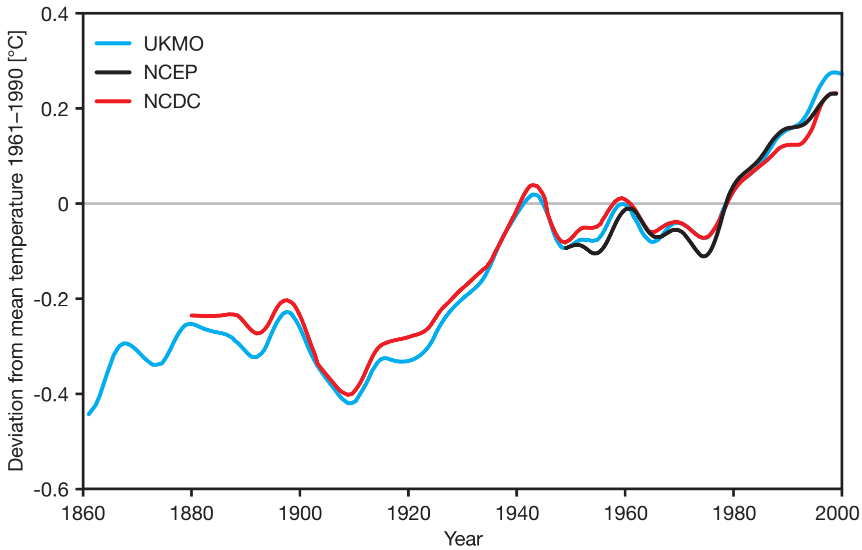


Figure 2.1-1
Globally averaged sea-surface temperature, according to three data centres: The UK Met Office (UKMO, blue), the US National Center for Environmental Prediction (NCEP, black), and the US National Climatic Data Center (NCDC, red). Source: IPCC, 2001a

2.1.2 Retreat of Arctic sea ice

An especially strong warming of seawater has been observed in the Arctic region in recent decades. This was described in 2004 in detail along with its impacts in an international study (Arctic Climate Impact Assessment; ACIA, 2005).

The study concludes that a significant reduction of the Arctic sea ice has occurred that can not be explained by natural processes but only by human influences. The ice retreat can be clearly seen in satellite photographs (Fig. 2.1-3). The satellite time series from 1979 to 2005 shows a decline in the ice area of 15 to 20 per cent. The lowest ice extent ever measured was recorded in September 2005. Using a compilation of observations from ships and coastal stations, this development can be extended back to the time before satellite measurements were available. These kinds of observations go back to the year 1900, and cover about 77 per cent of the area of the Arctic region. The long-term data strongly suggest that the present shrinking of the ice cover is a unique event in the past hundred years.

Changes in the thickness of Arctic ice are more difficult to observe than its lateral extent. With the end of the Cold War, measurements by military submarines that had patrolled beneath the Arctic ice became available. These data indicate that the ice thickness may have already decreased by 40 per cent (Rothrock et al., 1999). Other investigations suggest smaller decreases in the thickness. Johannessen et al. (2005) report a decrease of 8–15 per cent, so the actual changes still have to be regarded as uncertain.

Additional knowledge for the Arctic Ocean is obtained from computer models with high spatial resolution, driven by observed weather data. For

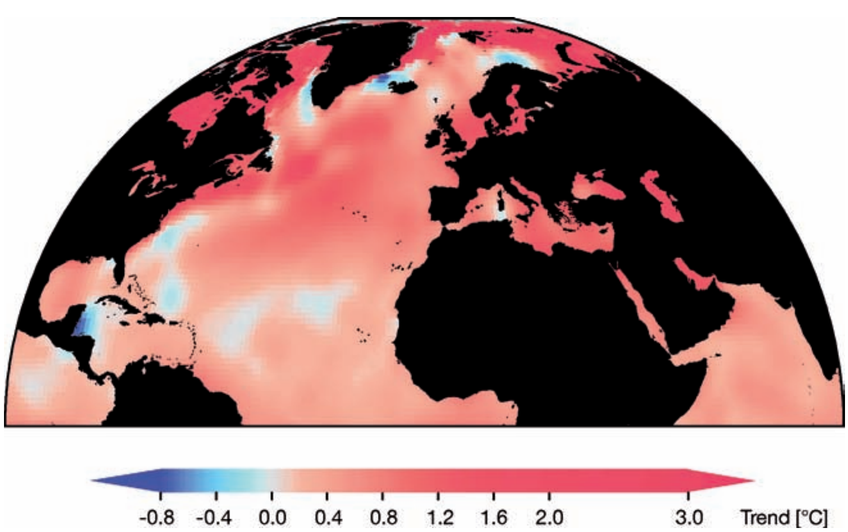


Figure 2.1-2
Development of sea-surface temperatures in the North Atlantic and European marginal seas. Temperature changes of the yearly average between 1978 and 2002 are shown (as a linear trend). Based on the GISST data set of the British Hadley Centre. Source: PIK, based on Hadley Centre, 2003

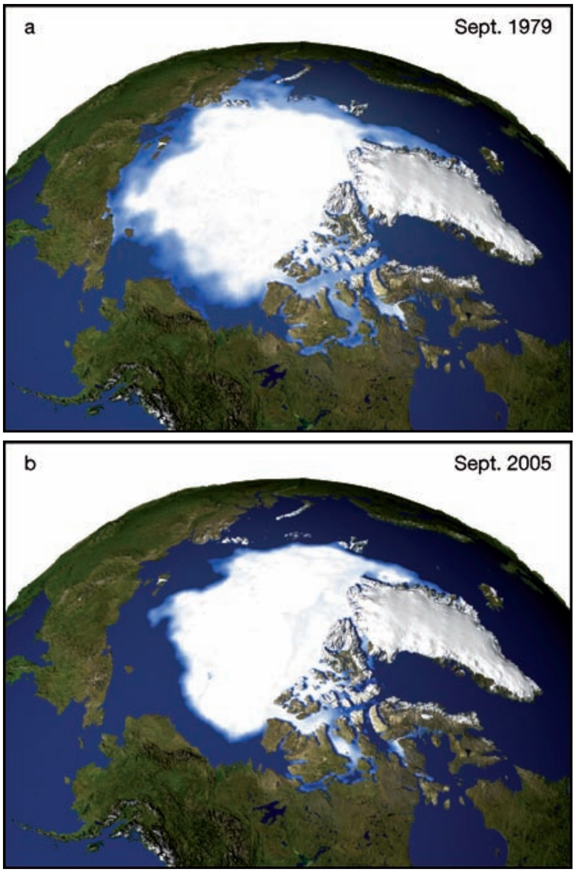


Figure 2.1-3
Satellite photos of the Arctic ice cover, (a) September 1979 and (b) September 2005.
Source: NASA, 2005

recent decades they show a decrease in ice extent that is in agreement with the satellite data as already discussed. In these models the ice thickness decreases more strongly, about 43 per cent since 1988 (Lindsay and Zhang, 2005). Maslowski et al. (2005) obtained similar numbers. If the warming continues unchecked, the scenarios produced by global models indicate that the Arctic Ocean will be practically ice-free in the summer by the end of this century (MPI für Meteorologie, 2005). According to the regional models mentioned, this condition could occur even earlier.

2.1.3
Changes in ocean currents

Since the 1980s scientists have begun to address the question of possible abrupt changes in Atlantic currents and their effects on the climate (Broecker, 1987). The basic problem – a possibly strong nonlinear response of the current to freshwater influx – was recognized as early as the 1960s (Stommel, 1961). In recent years there has been an increased focus by researchers on the probability and the possible impacts of such events. However, the research is still at an early stage and many questions have not yet been answered. The danger of changes in the marine currents was brought to the attention of the public through the 'Pentagon Report' by Schwarz and Randall (2003), which featured in the media in 2004. This report presented a worst-case scenario in which, during the next 10 to 20 years, the North Atlantic Current stops flowing, which would lead to a severe cooling in the North Atlantic region within just a few years. This is, however, a speculative and extremely improbable scenario. In the present situation there is no evidence to support an imminent change in the currents. But in the longer term, and with continued climate warming, this could develop into a serious danger by the middle of this century.

Huge masses of water currently sink from the surface to great depths in the Nordic Seas and the Labrador Sea. From there the water flows southwards at depths of 2–3km to the Southern Ocean (Figure 2.1-4). Balancing this loss of water, warm surface water flows from the south into the northern latitude regions. This results in a large-scale turnover of water in the Atlantic, in which around 15 million m^3 of water per second are transported. Like a central-heating unit, the ocean transports 10^{15} watts of heat to the northern Atlantic region through this process, which is equivalent to 2000 times the total output of Europe's power stations.

Global climate change affects this water flow by decreasing the density of seawater in two ways: first, the temperature increase causes a thermal expansion of the water and, secondly, increased precipitation and meltwater input dilute the seawater with freshwater. This density decrease can retard the sinking of water in the northern Atlantic, the so-called deep-water formation. Particularly in the Nordic Seas a salinity decrease has already been observed in recent decades (Curry and Mauritzen, 2005), although according to modelling calculations this trend is still too weak to have an impact on Atlantic current patterns.

British researchers have recently reported measurements suggesting that the circulation in the Atlantic may have already weakened by 30 per cent (Bryden et al., 2005). The interpretation of these data, however, is still contested in professional circles, in part because they do not agree with modelling calculations or with changes in sea-surface temperatures (Figure 2.1-2), where such a weakening of heat transport should be accompanied by a noticeable cooling. But if the trends of warming and salinity decrease should continue to strengthen in the coming

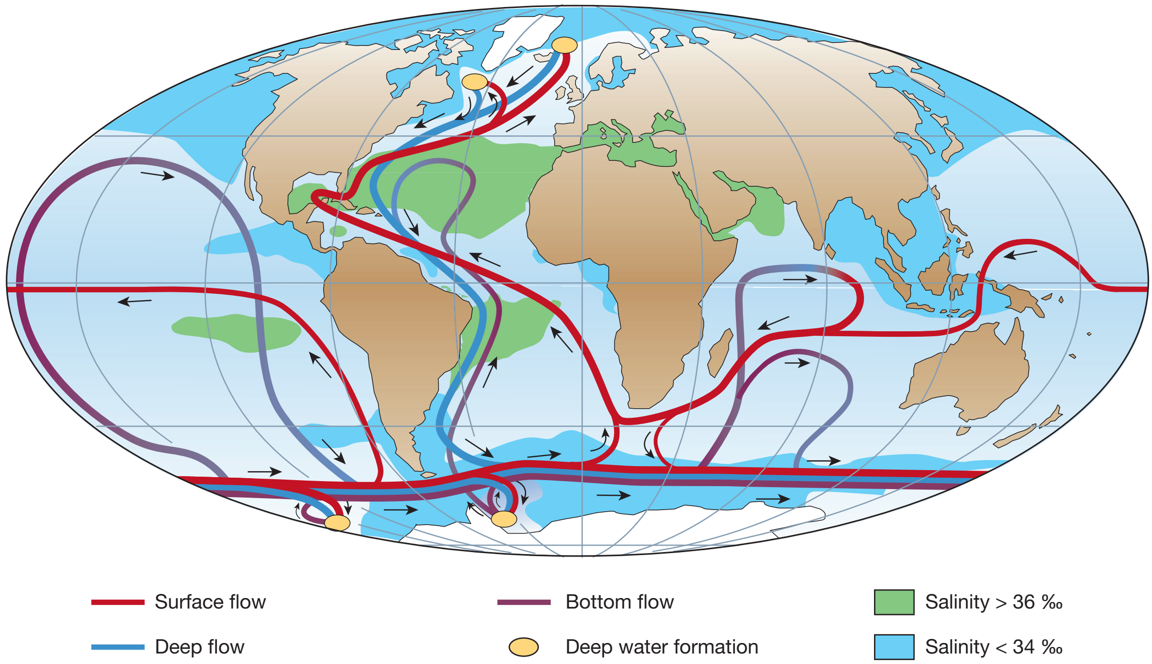


Figure 2.1-4
The system of global ocean currents, primarily showing the 'thermohaline' circulation that is driven by temperature and salinity differences.
Source: after Rahmstorf, 2002

decades, this may actually lead to a noticeable weakening of the Atlantic current over the course of this century, and in an extreme case possibly even to a total cessation of deep-water formation.

In all probability the consequences would be severe. The North Atlantic Current (not the Gulf Stream as is often too simply stated) and the greater part of the Atlantic heat transport would be shut down. This would significantly change the temperature distribution throughout the entire Atlantic region. Depending on the degree of warming that has taken place before, it could even lead to regional cooling to levels below today's temperatures. Southern Hemispheric warming would then be even stronger.

As a result of dynamic adaptation of the sea surface to the altered currents, sea level in the North Atlantic would quickly rise by up to 1m and slightly fall in the Southern Hemisphere. This redistribution of water would not have an immediate impact on the global sea-level average (Levermann et al., 2005). But over the long term the global average would rise by an additional 0.5m due to the gradual warming of the deep ocean after the loss of input of cold water. In addition, the tropical precipitation belt would very likely shift because the 'thermal equator' would drift southward (Claussen et al., 2003). This is indicated both by model simulations and historical climate data.

Initial simulation computations also show a reduction of the plankton biomass in the Atlantic by half (Schmittner, 2005; Section 2.2.2.2). Because of thermohaline circulation the Atlantic is presently one of the most fertile marine regions and most productive fisheries areas of the Earth. In addition, the interruption of deep-water formation would reduce the ocean's uptake of anthropogenic CO_2 (Chapter 4).

A breakdown of the North Atlantic Current is a risk that is difficult to calculate, but which would have severe adverse effects. One critical factor is the amount of freshwater that enters the northern Atlantic in the future. This will depend in large part on the speed at which Greenland's ice sheet melts. A reliable prediction is not possible with the present state of knowledge; at best, a risk estimation can be attempted. For this purpose the Potsdam Institute for Climate Impact Research together with the American Carnegie Mellon University questioned a dozen of the world's leading experts in the autumn of 2004, in detailed interviews lasting around six hours each. Their estimations of the risk of a total stop of deep-water formation and the associated currents varied considerably, but some were surprisingly high (Zickfeld et al., submitted). With an assumed global warming of only 2°C by the year 2100, four of the experts estimated the risk at greater than 5 per cent; with 3–5°C of warming, four of the experts indicated a risk exceeding 50 per cent.

2.2 Impacts of global warming on marine ecosystems

This section focuses on the impacts of climate warming (see Section 2.1) on marine ecosystems. WBGU considers this to include the entire marine realm, from the high seas to aquatically dominated coastal ecosystems. WBGU has deliberately only selected factors that are important to the subject of this special report. Overfishing, considered to be the most significant adverse anthropogenic impact today (Pauly et al., 2002; MA, 2005b), is not discussed. Also not treated here are direct destruction of marine ecosystems, pollution and alien species invasions (GESAMP, 2001; UNEP, 2002). Acidification of the sea is treated in Chapter 4. Togehter, these anthropogenic impacts have already strongly reduced the resilience of many marine ecosystems (Jackson et al., 2001).

The most productive areas in the oceans, the shallow continental shelves (<200m water depth) are the most intensely affected by these impacts. Although the shelves make up less than 7 per cent of the ocean's surface, this is where the greatest proportion of the primary and secondary production takes place, and where the most productive fishing grounds are found (Section 2.3). The primary production of the seas by algae (phytoplankton) is limited to the translucent upper water layer, the euphotic zone (down to approx. 200m water depth). A multitude of secondary producers live from these primary producers, especially zooplankton, fish and marine mammals, both in open water (pelagic) and at or below the sea floor (benthic). All organisms are linked to one another through a complex food web (Figure 2.2-1). For its energy source, the fauna of the dark deep sea is dependent on the organic carbon from the primary production, which sinks to the depths as dead biomass ('biological pump'). Only in the vicinity of hydrothermal vents in the deep sea do bacteria form an independent basis for higher life forms through chemosynthesis.

The coastal ecosystems are also of great biological and economical importance. In addition to their economic utility, some species-rich coastal systems such as wetlands, mangrove forests and coral reefs play a special role in protecting the coasts from flooding and erosion (Section 3.2).

2.2.1 Natural climate variability

The natural variability of abiotic factors in marine ecosystems such as water temperature or ocean currents is relatively great, and often follows non-linear or cyclic patterns. Studying the effects of natural climate variability can provide valuable information about the impacts of global warming. Compared to terrestrial systems, marine ecosystems react more sensitively and quickly to changes in climatic conditions, with unpredictable consequences for species compositions, spatial shifts of populations, or restructured food webs (Steele, 1998; Hsieh et al., 2005; overview by Brander, 2005). As Klyashtorin (2001) has shown, many Atlantic and Pacific fish stocks exhibit close correlations with climate patterns over many decades (Figure 2.2-2), for example, with the atmospheric circulation index, which describes atmospheric conditions in the Atlantic-Eurasian region. Even small natural climatic changes can have significant effects on marine ecosystems and fish stocks – through direct temperature effects, as a result of changes in primary production, or through impacts on important development stages (e.g., juvenile fish stages: Attrill and Power, 2002). For example, the cod stocks off Greenland reacted to a warming of the North Atlantic in the 1920s and 1930s with a rapid expansion to the north (approx. 50km per year) and a considerable increase of stock size, which later decreased again as a result of overfishing and deteriorating climatic conditions (Jensen, 1939). Plankton-feeding fish species in particular, such as sardines or anchovies, show strong natural stock fluctuations, in which large-scale climatic variations play an important role (Barber, 2001; PICES, 2004). The short-term disturbances of the ENSO events (El Niño/Southern Oscillation), for example, have far-reaching, 2- to 3-year effects on the marine ecosystems of the Peru-Humboldt current system (decreased nutrient supply causing lower primary production, partial collapse of fish populations: Barber, 2001) and on the most productive fish stock in the world (Peruvian anchovies: FAO, 2004; Bertrand et al., 2004). The impacts of the ENSO events are, however, reversible, with 'normal' conditions being re-established as a rule within a few years (Fiedler, 2002).

Ignoring small interannual variations, however, regional climatic conditions, along with the structure and dynamics of the ecosystems within a marine region, can also remain relatively stable over a period of many years or decades, defining what is generally referred to as a regime. When this kind of relatively stable situation changes rapidly, within the course of one or two years, it is called a 'regime shift' (King, 2005). Along with these regime shifts, considerable structural changes in the affected marine ecosystem occur, from the phytoplankton up to the highest trophic levels in the food web, including large predatory fish.

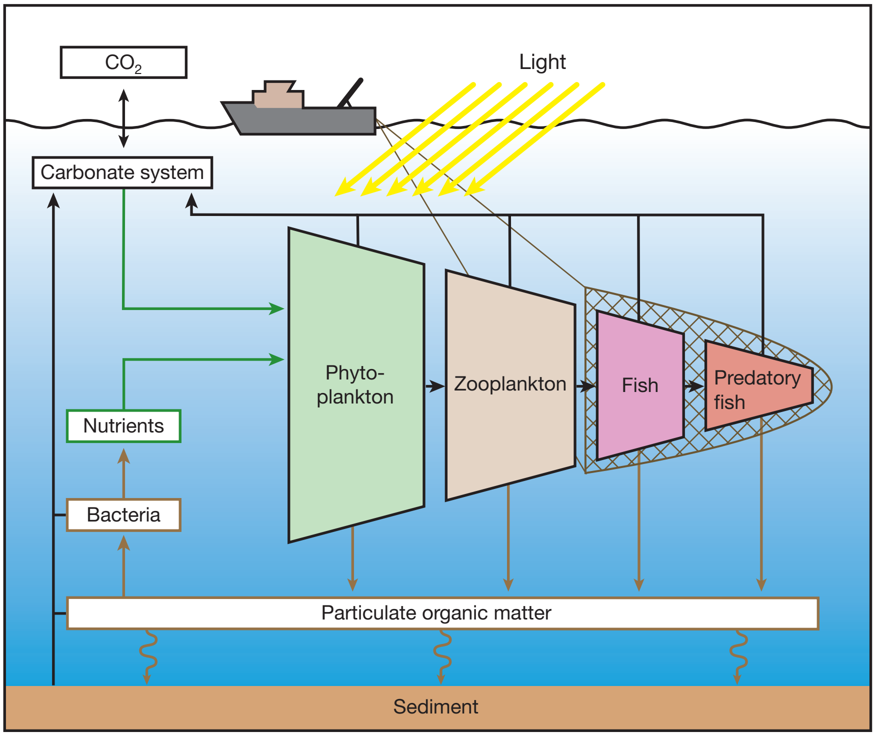


Figure 2.2-1
Schematic structure of a pelagic marine ecosystem. Green arrows: input to primary production; black arrows: interaction with the carbonate system; brown arrows: decomposition of biomass. In the interest of clarity, marine mammals and seabirds are not shown.
Source: WBGU

Regime shifts have been observed often and in various marine regions (King, 2005). In the North Sea in the late 1980s, for example, a regime shift occurred that was related to abrupt changes in surface temperature, wind conditions and a multitude of biological parameters (Reid et al., 2001; Beaugrand, 2004; Alheit et al., 2005). Due to an increase in westerly winds the influx of warm water into the North Sea was strengthened causing, among other things, a degradation of living conditions for North Sea cod. There is probably a connection between this persistent change in the North Atlantic Oscillation and anthropogenic climate warming (Gillett et al., 2003). In the North Pacific off the coast of California, alternating regimes with a period of around 60 years have been documented covering almost two millennia (Baumgartner et al., 1992). They cause a distinct restructuring of the marine ecosystems (Hare and Mantua, 2000; King, 2005).

How regime shifts are triggered and what effects they have in the food web of an ecosystem are not yet thoroughly understood, even though quite detailed observations of changing ecosystem structures do exist. The energy fluxes originating in the phytoplankton, at the base of the food web, often seem to play an important role ('bottom up' control: e.g., Richardson and Schoeman, 2004). However, structural changes can also be controlled 'top down', caused by the collapse of the population of predatory fish, either by overfishing (Worm and Myers, 2003; Frank et al., 2005) or by climatic changes (Polovina, 2005), and reaching down to the lower levels of the food web by trophic coupling.

2.2.2
Human-induced climate change

Although the natural variability can be very large regionally, the global warming trend already predominates in most areas (Figure 2.1-2). The anthropogenic impact on various climatic factors has already had observable effects on the distribution of marine organisms and the species assemblages of marine ecosystems (overview by Brander, 2005). Climate impacts have been described for all levels of the ecosystem, from primary production (Section 2.2.2.2) to zooplankton (e.g., Richardson and Schoeman, 2004) and small pelagic fish species (sardines), all the way up to the large predatory fish (tropical tuna: Lehodey et al., 2003).

2.2.2.1
Effects of water temperature on the physiology of marine organisms

According to the latest findings, temperature has a significantly greater influence on the distribution of animal and plant species than was previously assumed, and this is independent of the position of the organisms in the food web (Huntley et al., 2004).

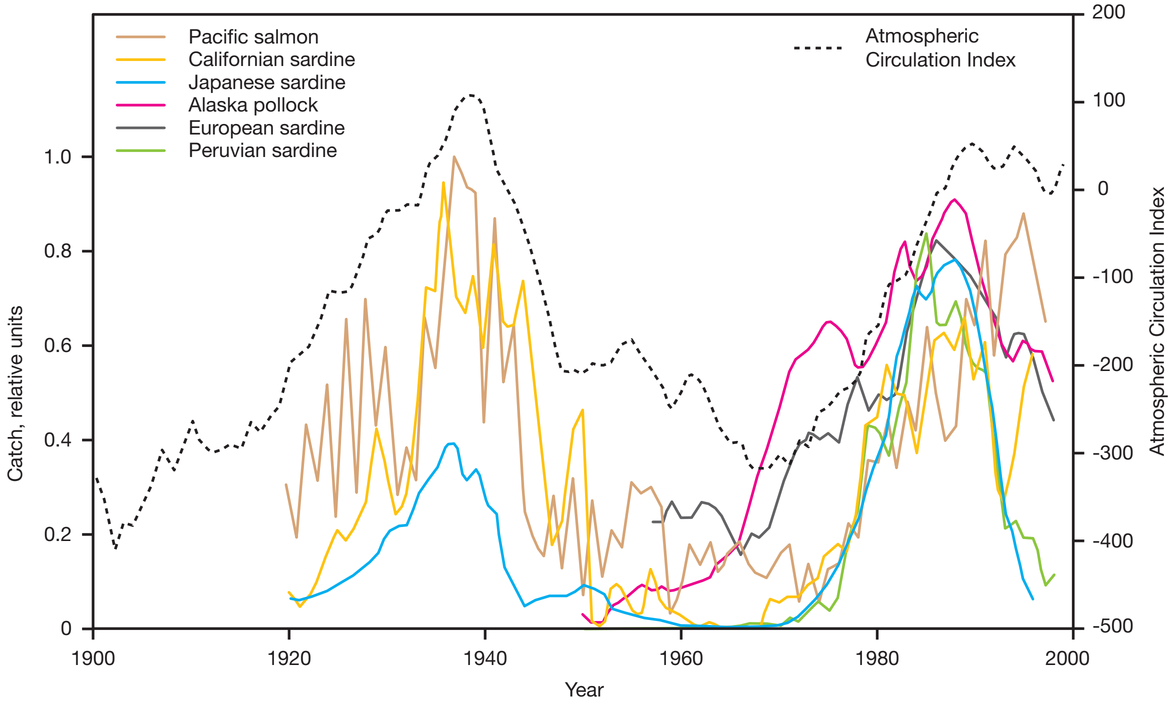


Figure 2.2-2
Correlation of the catch of various economically important fish stocks with the atmospheric circulation index.
Source: compiled on the basis of Klyashtorin, 2001

To a large degree, the window of thermal tolerance in which a species can survive, grow and reproduce determines its distribution (Pörtner, 2005). An increase in water temperature (Section 2.1.1) influences the life of marine organisms both directly and indirectly. A direct physiological impact is seen when the upper limit of the temperature tolerance range for a species is exceeded. This applies, for example, to tropical corals (Section 2.4.1). An indirect influence of increasing water temperature is observed, for example, when organisms previously available temporally and spatially as food for a species are no longer present due to changes in the species assemblage of an ecosystem caused by temperature differences (Section 2.2.2.5). Both of these effect chains can lead to shifts of populations, the invasion of alien species, and even the disappearance of species.

2.2.2.2 Phytoplankton and global primary production

The climatic factors altered by human activities (Section 2.1) initially affect the phytoplankton and therefore primary production. The total marine ecosystem, all the way up through the various trophic levels to the large predators such as tuna and sharks, feeds in principle from the primary production. Therefore, through this coupling, a change in primary production will have an effect on the higher trophic levels of the food web and will be reflected in changed species assemblages or biomasses in the total ecosystem. The primary production is influenced by many climatic factors (Fasham, 2003):

- *Temperature:* Growth and species composition of the phytoplankton are strongly dependent on temperature. Initially, primary production is directly stimulated through warming. But the increased temperature can also indirectly slow down production, for example due to a decrease in nutrient supply resulting from prominent temperature stratification.
- *Light:* Changes in the ice or cloud cover of the surface water have a direct influence on the primary production because the phytoplankton require light as an energy source. The light supply for phytoplankton also diminishes with increased mixing of the surface water.
- *Nutrients:* Climate change can also indirectly influence the supply of nutrients to the phytoplankton (primarily nitrogen and phosphorous, but also 'micronutrients' such as iron: Jickells et al., 2005). Through the sinking of dead organisms from the productive upper layer of the ocean, organic material and thereby nutrients are continuously exported to the deep sea ('biological

pump': Falkowski et al., 2003). The return transport to the upper layers occurs through upwelling currents and vertical mixing, which are influenced by climate in the form of temperature stratification, as well as wind and current conditions (for example, Sarmiento et al., 2003).

In addition to all these factors, climate warming is largely a result of rising CO_2 concentrations. In many phytoplankton species this leads to a direct increase in the rate of photosynthesis, although the various species groups benefit to differing degrees (Section 4.3.1). These various factors are also all coupled with one another. The warming of the surface layers not only increases photosynthesis rates, it also promotes a more stable layering of the water column, which decreases the nutrient supply and weakens the plankton production. The stronger stratification can also destabilize the dynamics of phytoplankton production (Huisman et al., 2006). An increased wind speed, on the other hand, counteracts the temperature effect upon stratification. In the northeast Atlantic the sum of these counteracting effects produces a net increase of phytoplankton in cold-water regions (because here with the good nutrient supply and higher turbulence the improved metabolism rates due to temperature increase are predominant), and a net decrease in warm-water regions (because stronger stratification, under limited nutrient availability, worsens the growing conditions; Richardson and Schoeman, 2004). It is therefore not surprising that these effects are difficult to model and vary greatly from region to region.

Satellite-based observations of the phytoplankton biomasses derived from the chlorophyll content of seawater reveal that the global annual primary production has decreased in nine of twelve ocean regions since the 1980s, and the global average by more than 6 per cent (Gregg et al., 2003). The high northern latitudes account for 70 per cent of the global decline, presumably caused by the worsening nutrient supply due to the rise in temperature. Only three tropical ocean regions (northern and equatorial Indian and the equatorial Atlantic) exhibited an increase. For the North Atlantic, long-term data series based on physical samples show an increase in phytoplankton north of 55°N and a decrease south of 50°N (Richardson and Schoeman, 2004). The projections for a future with global warming show contradictory trends. The modelling of Bopp et al. (2001) suggests a reduction of the global marine export production (which correlates well with primary production) by about 6 per cent in the next 65–75 years with a doubling of the atmospheric CO_2 concentrations. Production in the tropics would decline due to stronger stratification and the resulting decrease in nutrient supply, while increasing in the subpolar regions. In contrast, the models of Sarmiento et al. (2004), with large uncertainty, show a slight increase in the global primary production. Again, the effects are regionally highly variable. The authors of the Arctic Climate Impact Assessment consider it probable that moderate warming would promote primary production in the Arctic, mainly due to the reduction of sea ice (ACIA, 2005).

So the available findings are, at least in part, contradictory, and regional observations are not always in agreement with model prognoses. Obviously, our understanding of the critical processes, such as the temperature sensitivity of primary production, is insufficient. The quality of coupled climate, ocean, and ecosystem models presently does not allow any robust conclusions (Sarmiento et al., 2004), although some regional models are already able to represent the connections between the changes in ocean currents and primary production (examples in Brander, 2005).

It is improbable that climate change will lead to the breakdown of the North Atlantic Current, but this possibility cannot be excluded (Section 2.1.3; Rahmstorf, 2000; Curry and Mauritzen, 2005). The simulations of Schmittner (2005) show a completely altered ecosystem situation for this scenario: the biomasses of phyto- and zooplankton in the North Atlantic would decrease by half due to sharply reduced nutrient supply in the surface waters, with corresponding large impacts on ecosystem productivity and structure.

2.2.2.3 Zooplankton

Primary production by phytoplankton is the nutritional basis for the zooplankton (secondary production: often small crustaceans), which is in turn significant as food for the growth of fish populations. Fish larvae in particular are dependent on the synchronous and high availability of appropriate zooplankton, so that fish stocks can replenish and production is maintained. The following examples show that for the zooplankton too, noticeable changes can already be identified as a result of anthropogenic climate change.

In the North Atlantic the distribution of copepods, an important group in the marine food web, has shifted to the north by around 10° of latitude as a result of a combination of changes in the North Atlantic Oscillation (NAO) and human-induced climate change (Beaugrand et al., 2002). For the North Sea cod these changes, along with overfishing, have contributed to poor conditions encountered by the fish larvae and a steady decline of the population (Beaugrand et al., 2003).

Krill (*Euphausia superba*) in the Antarctic have declined significantly since 1976, while other zooplankton species (salps) have increased, which can probably be attributed to the climate-driven reduction of sea ice around the Antarctic peninsula (Atkinson et al., 2004). Because krill is an important food source for fish, penguins, seals and whales, this has led to significant changes in the food web in the Southern Ocean. Investigations of planktonic foraminifera in sediments covering the past 1400 years have revealed an anomalous change in the species assemblages in recent decades. This suggests that the anthropogenic warming of the ocean has already exceeded the range of natural variability (Field et al., 2006).

2.2.2.4 Marine mammals

The warming also causes a decrease in the geographic extent of the Arctic sea ice. This especially affects animals such as polar bears and ringed seals, which are directly dependent on this habitat in their feeding habits and for the rearing of their young (ACIA, 2005).

Polar bears feed almost exclusively on seals, which are bound to the ice habitat. Female polar bears bear their young in caves on the land. In the spring after their winter sleep, in order to reach their hunting areas on the ice, the mother and her young are dependent on ice corridors, because the young animals cannot cross large areas of open water. If the ice continues to recede, they will not be able to reach their hunting grounds. Adult polar bears are good swimmers, and can cover distances in the water of over 100km. Monnett et al. (2005), however, report a doubling of the number of polar bears sighted swimming in open water within a 20-year observation period, as well as most recent finds of four drowned polar bears near Alaska in a location where the ice was over 200km to the north of its normal seasonal limit. Around Canada's Hudson Bay, the area of their southernmost occurrence, the polar bear population has declined by 22 per cent since 1987 (Carlton, 2005). With the loss of the summer sea-ice cover, polar bears are forced into a life on land, where they encounter competition with brown and grizzly bears and increased contact with humans, which reduces the chances for survival of this species.

Scenarios for the Baltic Sea also indicate that the ice cover here will significantly decrease over the next 30 years. The Baltic ringed seal requires a firm ice layer with a snow cover for at least two months for rearing its young. Of the four former breeding areas in the Baltic Sea with separate populations only one suitable area will remain available in the future: the northern Bay of Bothnia (Meier et al., 2004). Initial observations have been reported in the Antarctic, too, that can be attributed to climatic changes. For the past 20 years birth rates of the cape fur seal have been in decline. This decrease correlates with unusually high temperatures of the surface water subsequent to the abundant El Niño events between 1987 and 1998, and it has presumably been intensified by the lowered nutrient supply – primarily krill – for the female seals (Forcada et al., 2005).

These examples illustrate how changes in the ice habitat caused by climatic change can drastically impact the highest trophic levels.

2.2.2.5 Ecosystem impacts

Temperature increases and other factors related to climate change affect groups of organisms in different ways, so that population shifts can occur at different rates and intensities to separate species that previously inhabited the same region or were present at the same time. This decoupling of previously synchronous trophic levels ('trophic mismatch') can produce considerable changes in the ecosystem structure (for example, in the North Sea: Edwards and Richardson, 2004). Climate-induced spatial changes in the phytoplankton distribution can affect both the herbivorous zooplankton and the carnivorous zooplankton, so that fish, seabirds and mammals also have to adapt to the new conditions (Richardson and Schoeman, 2004).

These kinds of large-scale shifts have already been observed at different levels in the food web, for example in the North Atlantic (Beaugrand and Reid, 2003). After an anomalous temperature increase in the 1980s, populations of cold-water species such as euphausids and copepods shifted northward and the stocks decreased, while the smaller warm-water species showed a corresponding increase (Beaugrand et al., 2002). This then led to a decline in the salmon population. For the future, Beaugrand and Reid (2003) expect a continuing decline in the number and distribution of the salmon population, especially at the southern edge of its geographic distribution (Spain and France).

As a result of the displacement of distribution areas of many species toward the poles, the pressure on marine ecosystems increases in the polar regions due to the immigration of new species, while the inhabitants of these regions, adapted to cold temperatures, cannot move to cooler latitudes. They are therefore particularly sensitive to climate change, so that losses of habitats and species are to be expected, especially in the polar marine sea-ice ecosystems (Smetacek and Nicol, 2005; ACIA, 2005). In addition, regional expressions of global warming are especially evident in the Arctic, in part because there is a particularly strong feedback with regional temperatures there as a result of the albedo changes due to retreating sea ice.

It is likely that primary production in the Arctic Ocean will increase due to climate warming, albeit from a low initial level (ACIA, 2005). The increased production can either be exploited by the zooplankton or fall out as sedimentation and provide nutrients for the benthic fauna. In regions with seasonal ice cover, a temporal shift could occur between the phytoplankton bloom and the massive occurrence of zooplankton as well as between the zooplankton and fish larvae due to the climate-dependent changes in the start of ice melting in spring. Such a lack of synchronization would result in a lower share of the primary production being available for higher levels of the food web. Reliable predictions cannot be made, however, concerning the effect of increased primary production on fish, bird and mammal populations (ACIA, 2005).

An important question is whether anthropogenic climate change can influence naturally occurring regime shifts (Section 2.2.1). With the low resilience of marine ecosystem structures and the intensity of expected anthropogenic climate signals (Section 2.1.1) the possibility that regime shifts in the future will exhibit a different quality, occur more often or rarely, or occur in regions where they have not been previously seen can absolutely not be excluded. The observed acceleration in the periodicity of regime shifts in the North Pacific (King, 2005) could be indicative that there is a link with anthropogenic climate change, although a conclusive judgement cannot be made at this time (Brander, 2005).

The new findings in marine ecology support the increased climate change mitigation efforts that have been called for in previous WBGU reports (e.g. WBGU, 2003), because if climate warming continues unchecked, severe unpredictable and undesirable changes in marine ecosystems cannot be discounted.

2.3 In focus: Climate and fisheries

For over 2600 million people fish is the basis of at least 20 per cent of their protein supply (FAO, 2004). Industrial fisheries are growing and are coming into increasing competition with the 30 million traditional fishers, who are often faced with losses in income (World Bank, 2004). World fish production in recent years has remained stagnant at around 130 million tonnes per year, whereby the proportion of fish caught in the sea has slightly decreased and the share of aquaculture has risen (FAO, 2004). Fish stocks are very unequally distributed in the sea: less than 7 per cent of the ocean's area is represented by the continental shelves (water depths <200m), but these account for more than 90 per cent of the global fish catch (Pauly et al., 2002).

At the same time, the human impact on the marine ecosystems of the continental shelves is especially great: overfishing (FAO, 2004; MA, 2005b), including illegal or unregulated fishing (Gianni and Simpson, 2005), degradation and destruction of marine and coastal habitats (such as corals, Section 2.4), the invasion of alien species, pollution of the world's oceans (GESAMP, 2001), and, as a new threat, acidification (Chapter 4) endanger the health of the ecosystems and the sustainability of their use. Poor fisheries management and resulting overfishing are certainly more critical factors for the fish stocks than the anthropogenic climate change observed so far (Worm and Myers, 2004; ACIA, 2005). In the future, however, the latter could also cause a considerable additional burden for marine ecosystems (IPCC, 2001b; Richardson and Schoeman, 2004; Section 3.1.4).

2.3.1 Changes in fish populations

Similar to the terrestrial realm, the species in marine ecosystems often respond to anthropogenic warming with a poleward shift (Parmesan and Yohe, 2003). This is also the case for many of the fish populations in European shelf waters, with increasing evidence of a northward shift due to warming (Fig. 2.3-1). The stocks of cod in the North Sea are decreasing at a rate that cannot be explained by overfishing alone. Today, the upper limit of the thermal tolerance window has already been reached there, with the result that populations are moving northward. The decrease of cod correlates significantly with the changed species assemblage, stock decline and smaller average body size of the zooplankton (Beaugrand et al., 2003), which can probably be attributed to climate change. Fundamental changes in the pelagic ecosystem have been observed in the North Sea from 1925 to 2004, with a clear shift of many populations northward and the immigration of southern species (Beare et al., 2004). These systematic long-term trends correlate with the rising sea temperature. From observations in the North Sea, Perry et al. (2005) conclude that a further increase in temperature will result in additional changes in the species composition and ecosystem

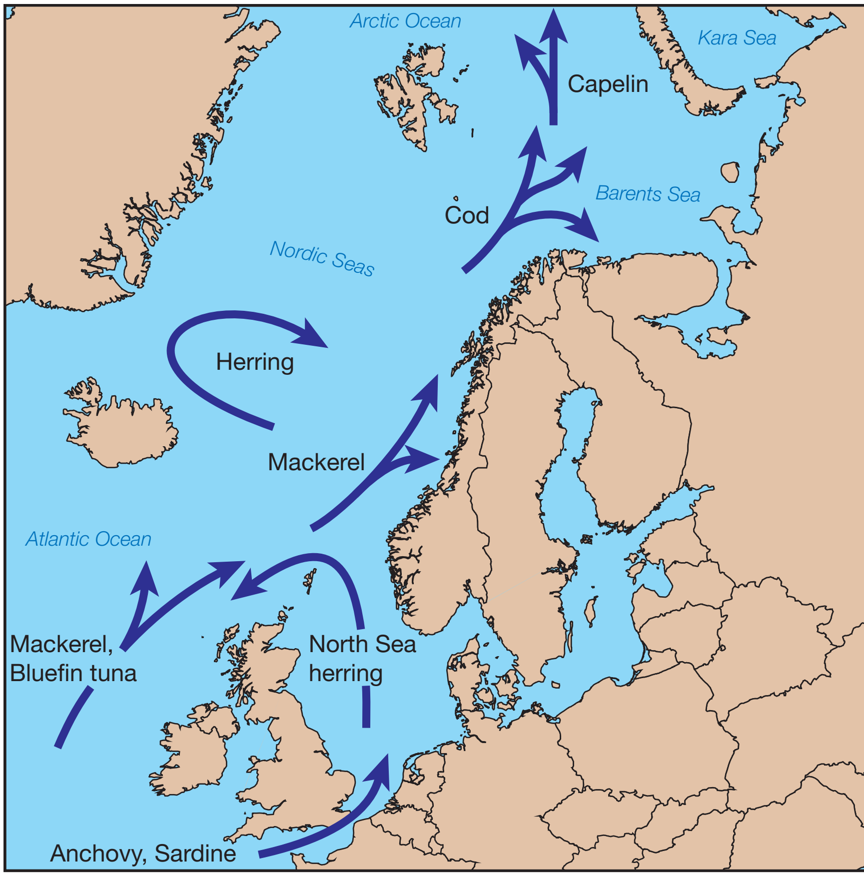


Figure 2.3-1
Likely extension of the feeding area for some of the main fish populations if sea temperature increases. Source: ACIA, 2005 modified after Blindheim et al., 2001

structure that cannot be predicted in detail, but will probably put considerable adaptive pressure upon commercial fisheries. In various Arctic marine regions, with a regional warming of 1–3 °C, northward displacements of fish populations can be expected, along with the establishment of discrete populations (e.g., cod near Greenland) as well as the immigration of southern species (ACIA, 2005).

2.3.2 Regional prognoses of impacts on fisheries

For some marine regions, especially for waters in the northern latitudes, our understanding of the ecosystem structures and their response to natural climate variability is good enough to discuss possible impacts of climate change. The Norwegian Sea, for example, is a very well studied area (Skjoldal, 2004). Based on experience with natural climate variability it can be assumed that regional temperature increases of 2–4 °C could increase the primary and secondary production of the sub-Arctic part of the Norwegian Sea and therefore improve conditions for fish production (Skjoldal and Sætre, 2004). At the same time, however, the spectrum of species would experience a shift, i.e. warm-water southern species would be introduced to the area.

The authors of the Arctic Climate Impact Assessment (ACIA) also assume that a regional warming of 1–3 °C would improve the conditions for some economically important fish populations, such as Atlantic cod or herring, because the retreat of sea ice would increase both the primary and secondary production as well as allowing these species to spread northward (ACIA, 2005).

Regime shifts with distinct changes in species composition (Section 2.2.1) are not ruled out by the ACIA, but its authors deem that the adaptation of the fisheries sector to the new conditions should not present a great expense. The ACIA comes to the general conclusion that the type and effectiveness of fisheries management – in particular the prevention of overfishing through application of the precautionary principle – will have a greater impact on production in the Arctic than the moderate regional climate change of 1–3 °C that is projected for the 21st century. Accordingly, significant economic or social effects at the national level are not expected, even though individual Arctic regions that are heavily dependent on fisheries could be clearly impacted.

This assessment changes, however, in the case of a more substantial regional climate change (>3°C). While the authors of the ACIA consider it possible that negative consequences could result for fisheries in some Arctic marine regions, they hesitate to make predictions for most Arctic regions due to the incomplete understanding of ecosystem structure and dynamics. Although the Arctic waters have been comparatively well studied, no reliable ecosystem model coupled with climate scenarios currently exists. The assessment of ecosystem impacts therefore must remain speculative. In order to answer the remaining questions, research efforts will have to take a more ecosystem-based approach. Improved numerical ecological models based on integrated environmental monitoring will make an important contribution (Skjoldal and Sætre, 2004; Section 2.7).

2.3.3 Global prognoses of impacts on fisheries

The Food and Agriculture Organisation of the United Nations (FAO) refers to future anthropogenic climate change as an example of the uncertainty justifying a precautionary approach to fisheries management (FAO, 2000). In its report 'The State of World Fisheries and Aquaculture 2002', FAO draws attention to the importance of natural long-term climate variability for the development of fish stocks in a chapter dedicated to this subject. It also points out that global warming could have significant impacts – positive or negative – on some, if not most of the commercial fish stocks (FAO, 2002). It concludes that stocks drastically reduced by overfishing are more vulnerable to climatic changes than sustainably exploited stocks (FAO, 2004). However, FAO's long-term projections are, even today, still based *inter alia* on the assumption that environmental conditions, including the climate, are not changing significantly.

The Intergovernmental Panel on Climate Change (IPCC, 2001b) points to the increasingly acknowledged relationship between natural climate variability and the dynamics of fish stocks and concludes that global warming complicates these relationships and will make fisheries management more difficult. Climate change therefore has the potential, during the coming decades, to become an important factor in the management of marine resources, although the effects will vary widely depending on the region and ecosystem characteristics (IPCC, 2001b).

The authors of the Millennium Ecosystem Assessment also warn about the consequences of climate change, although they have not carried out a detailed analysis. They describe current knowledge about the effects of climate change on marine ecosystems as inadequate. They point out in particular that the response of fish stocks to environmental influences depends, not least, on population size. Healthy stocks with large production of fish larvae can adapt better to population displacement and changes in ecosystem structure. Stocks that are greatly reduced due to overfishing respond more sensitively to environmental influences such as climate change (MA, 2005b) because there is a greater probability that the minimum stock level for reproduction is not attained.

Despite the lack of scientific data, several general recommendations for the management of marine ecosystems and fisheries management can be made. These will be discussed in Section 2.6.

2.4 In focus: Climate and coral reefs

Tropical coral reefs are recognized as the most species-rich of marine biotopes, not so much because of the abundance of species of the reef-building corals themselves (over 835 species have been described), but because of the biological diversity of organisms that live on and from coral reefs, representing an estimated 0.5–2 million species (Reaka-Kudla, 1997). Coral reefs provide important products such as fish and building materials (blocks of coral limestone). They also offer protection from the effects of tsunamis and coastal erosion, and at the same time, because of their aesthetic and cultural value, they are an important source of income from tourism. Although coral reefs only cover 1.2 per cent of the global continental shelves, it is estimated that more than 100 million people are economically dependent on them (Hoegh-Guldberg, 2005). A status report on worldwide coral reefs (Wilkinson, 2004) provides information on their development since the 1950s and raises vital concerns with its estimation of the future trends:

- 20 per cent of all coral reefs have been effectively destroyed and show no immediate prospects of recovery,
- 24 per cent of all coral reefs are under imminent risk of collapse through human pressures,
- a further 26 per cent are under a long-term threat of collapse.

The changes of the past 20–50 years are referred to as the 'coral reef crisis' because the adaptive capacity of corals and the animals and plants associated with them to changing environmental conditions has been exceeded worldwide (Hoegh-Guldberg, 1999; Pandolfi et al., 2003). The pressure from human activities is locally generated, first through poor land management practices, whereby sediments, nutrients and pollutants are released and washed into the sea and damage the reefs. In addition, overfishing, primarily the fisheries using destructive methods (dynamite, cyanide, heavy fishing rigs), reduces the populations of key species on the reef, damaging the function of the ecosystem and reducing productivity. After ecosystem damage, macroalgae have an advantage over the coral in their growth because the feeding pressure by selectively caught fish that normally feed on these algae declines.

In addition to the local stress factors, two results of global climate change are becoming increasingly important to the condition of coral reefs and will therefore be investigated in more detail in this section: the increase in seawater temperature and the acidification of seawater. These two factors contribute individually as well as synergistically, together with the local anthropogenic stressors, to the destruction of coral reefs.

It is only in recent decades that coral reefs were also discovered to exist in deep, dark, cold-water zones in practically all of the world's oceans (Freiwald et al., 2004). Their ecosystems and the serious dangers to them, particularly from bottom-trawl fishing, are currently being researched. Whether they are also threatened by the effects of climatic changes such as temperature change and changes in the availability of calcium carbonate is not clear.

2.4.1 Warming impact on corals

Coral reefs dominate tropical coasts at latitudes between 25°N and 25°S, which corresponds to a seawater temperature range of 18–30°C (Veron, 1986). Along with the atmosphere, the surface layers of the ocean have also warmed in recent decades (Section 2.1.1). In seven tropical regions where corals occur, a warming of 0.7–1.7°C has been measured in the 20th century (Hoegh-Guldberg, 1999).

Since 1979 a new phenomenon has been described with increasing frequency and geographic extent, called coral bleaching. This refers to the loss of single-celled algae that live in symbiosis with the corals. If a coral is subjected to a stress situation, which either in nature or in the laboratory can be produced by high or low temperatures, intensive light, changes in salinity or other physical, chemical and microbial stress factors, the algae will be expelled from the coral tissue. The living tissue of the corals is transparent without algae cells, so the white limestone skeleton will show through – hence the term coral bleaching. This phenomenon is to some extent reversible because algal cells can be taken up again by the body tissue. But after extended periods of coral bleaching the corals die.

Abundant occurrences of coral bleaching were first described in the scientific literature in the early 1980s. Strongly increasing worldwide occurrences correlate with higher surface temperatures of seawater and with disturbances related to El Niño events (El Niño/Southern Oscillation, ENSO). The most intense event by far occurred in 1997–1998, resulting in the death of 16 per cent of all tropical corals worldwide. Regionally the values were even higher, e.g. at 46 per cent in the western Indian Ocean (Wilkinson, 2004).

The strength and duration of the temperature anomalies are important values for predicting coral bleaching. The 'Degree Heating Weeks' (DHW), which aggregate the thermal stress over 12 weeks, were developed as an indicator. One DHW is equal to one week with a temperature of 1°C above the summer maximum during the previous 12 weeks. The USA's National Oceanic and Atmospheric Administration (NOAA) provides an operational early warning system for this. Analyses of the measurement series show that 8 DHW led to coral bleaching in 99 per cent of all cases. Coral bleaching can be predicted today with over 90 per cent probability several weeks before the event occurs (Strong et al., 2000). The worldwide area of coral reefs affected by DHW >4 is continuously increasing (Wilkinson, 2004). Modelling calculations based on IPCC scenarios indicate that between 2030 and 2050 events similar to the anomalous year of 1998 could occur annually, spelling the end of coral-dominated ecosystems (Hoegh-Guldberg, 2005). By combining the data of the NOAA early warning system with global circulation models, Donner et al. (2005) arrived at similar conclusions. According to their research, in 30–50 years coral bleaching will occur every one to two years in the large majority of all coral reefs if the corals do not adapt their temperature tolerance by 0.2–1°C per decade.

An important observation is that the threshold value of seawater temperature for triggering coral bleaching at many locations is only 1–2°C above the maximum summer temperature. Tropical corals are therefore living very close to the highest temperature at which they can survive (Hoegh-Guldberg, 1999). Assuming that the near-surface seawater temperatures will continue to increase, the question is how corals could respond to this temperature increase. Hughes et al. (2003) describe possible responses: a single threshold value for all coral species is unlikely; instead, the threshold values vary within a certain bandwidth depending on coral species, water depth and location. A model in which the different threshold values for the demise of the corals change with time through acclimatization and evolution seems to be most realistic. Symbiotic algae that occur in various genotypes are adapted to different upper temperature limits, for example. After coral bleaching has occurred, heat-tolerant algal groups could be taken up into the coral tissue, offering improved protection against future temperature peaks, and thereby providing some limited adaptation to climate change (Baker et al., 2004; Rowan, 2004). Hoegh-Guldberg (2005), however, expresses the concern that the evolutionary adaptation of corals and algae cannot keep pace with the rapid environmental changes taking place over just a few decades.

Coral reefs could also respond to increased seawater temperatures with a shift of their distribution or a change in their species assemblage. A poleward displacement of the distribution region, however, could only amount to a few degrees of latitude at most, because both the light (for photosynthesis of the symbiotic algae) and the aragonite supersaturation (for calcification) are limiting factors (Buddemeier et al., 2004).

2.4.2 Acidification impact on corals

The acidification of the sea through hydrolysis of CO_2 in seawater (Section 4.1) influences the carbonate chemistry and thereby also affects the corals, which produce skeletons of calcium carbonate (Orr et al., 2005). The formation of limestone (calcification) is not only the foundation for the growth of the coral reefs but also helps to counteract the process of reef erosion. The CO_2-determined impairment of calcification hampers the spread of coral reefs to cooler marine regions. Consequently, both increased temperatures and increased CO_2 concentrations must be expected to drastically constrain the distribution areas of the present-day coral reefs (Hoegh-Guldberg, 2005).

In laboratory experiments simulating a doubling of the CO_2 concentration in the atmosphere, the calcification rate for corals dropped by 11–37 per cent (Gattuso et al., 1999). Modelling calculations by Kleypas et al. (1999) confirm these results. According to their findings, calcification today has already fallen by 6–11 per cent compared to pre-industrial rates. With a doubling of CO_2, a further drop of 8–17 per cent compared to today's rates was calculated. Decreased calcification results in slower expansion of the coral skeleton and therefore a decreased competitive capacity for space in the coral reef. In addition, skeletons of lower density are produced, which are more delicate and vulnerable to erosion.

The calcification rate is influenced not only by CO_2 concentrations but also by water temperature. Increased seawater temperatures can lead to higher metabolic activity and increased photosynthesis rates of the symbiotic algae and thus to increased calcification by the corals (Lough and Barnes, 2000). McNeil et al. (2004) conclude from in-situ investigations and model calculations that the calcification rates of corals in the year 2100 could be at as much as 35 per cent above the pre-industrial rates in spite of decreasing aragonite saturation due to marine warming, presuming an adaptation of the corals to higher seawater temperatures. These hypotheses are scientifically contested (Kleypas et al., 2005). For calcification to increase over the long term the temperature rise of seawater has to remain below the thermal tolerance limit of the corals. So the key question here is whether the tropical corals and their symbiotic algae can genetically adapt their temperature tolerance quickly enough to keep pace with rising seawater temperatures. The question of possibly increased calcification would be moot if the corals die from heat stress.

2.4.3 Measures for coral conservation

Due to the specialization of tropical coral reefs within a narrow range of temperatures, aragonite supersaturation, and high light availability conditions, climate change, in addition to local anthropogenic stress factors, poses a great threat to them. Increasing occurrences of coral bleaching highlight the need for rigorous implementation of climate policy measures. Even the healthiest reefs are not immune to these impacts, as the status report on coral reefs points out (Wilkinson, 2004). It has, however, been found that 'healthy' reefs located in pristine areas have the greatest chance of surviving coral bleaching episodes. So it makes good sense to strengthen the resilience of coral communities through protective measures.

For this purpose the establishment of marine protected areas (MPAs) is considered to be especially effective, preferably in their most stringent form as No-Take Areas, which are closed to fishing (Hughes et al., 2003; Bellwood et al., 2004; Section 2.6.2). The focus on protected areas, however, should not lead to neglect of the remaining much larger reef areas that are not designated as protected. The critical functional groups (communities of particular, often regionally different species that maintain the ecosystem) have to be protected at a regional level; otherwise, the area loses resilience.

2.5 Guard rail: Conservation of marine ecosystems

2.5.1 Recommended guard rail

The guard rail concept devised by WBGU helps to operationalize the guiding principle of sustainable development (Box 1-1). A guard rail for conservation of marine ecosystems can be developed, although it will inevitably be temporary in nature because the scientific basis remains weak. Analogously to the ecological guard rail recommended by WBGU (2001) for terrestrial land and freshwater ecosystems, the Council recommends that at least 20–30 per cent of the area of marine ecosystems should be designated for inclusion in an ecologically representative and effectively managed system of protected areas.

2.5.2 Rationale and feasibility

The rationale behind this guard rail is, among other things, the realization that ecosystems and their biological diversity are vital for the survival of humankind because they fulfil a great variety of functions and provide a whole range of products and services (MA, 2005b). Ecosystem conservation is therefore an indispensable component of sustainable development. In its biosphere report, WBGU (2001) developed five principles that can provide a basis for sustainable management of ecosystems and serve as a background for developing a guard rail for protection of marine ecosystems: (1) preserve the integrity of bioregions; (2) safeguard biological resources; (3) maintain biological potential for the future; (4) preserve the global natural heritage; (5) maintain the regulatory functions of the biosphere.

Protected near-natural marine ecosystems fulfil many important functions for human society (Section 2.6). They play a major role in coastal protection (e.g. protecting coasts from sediment losses, wave erosion and flooding; Section 3.2), water purification, as a fisheries management instrument (Gell and Roberts, 2003; Section 2.6.2.1) and in tourism. They are also indispensable for conserving biological diversity and increasing the resilience of marine ecosystems to anthropogenic stress factors.

Developing a marine protected areas network by the year 2012 has now become an internationally recognized goal (Section 2.6.2.2). Although there is no dispute regarding the normative principles and the value or services provided by marine ecosystems, and the need to protect them, it is very difficult to translate this into a quantitative guard rail because the scientific basis for such quantification remains weak. Moreover, a simple global ‘protection standard’ is unlikely to meet the needs of different regions with vastly diverse ecological assets and situations. A standard of this sort can therefore only serve as a rough yardstick; it cannot be applied directly to all regions (Bohnsack et al., 2002; Agardy et al., 2003; Rodrigues et al., 2004). Conversely, the current practice of leaving almost all marine and coastal ecosystems open to overexploitation or destruction is certainly not a situation that can be considered tolerable. For this reason, a global guiding principle should be established that helps communicate the considerable deficits that currently exist and make initial progress at least towards slowing the continuing destruction of the natural resource base.

The IUCN World Parks Congress recommended protecting 20–30 per cent of each type of marine habitat (WPC, 2003a), and in the Convention on Biological Diversity this was also the target under consideration, although in the end it was not approved (CBD, 2003). At national level, similar coverage targets are under discussion: USA: 20 per cent (NRC, 2001), Great Britain: 30 per cent (Royal Commission on Environmental Pollution, 2004); the Bahamas, Canada and the Philippines, for example: 20 per cent (Agardy et al., 2003). Australia has demonstrated that these figures are not unrealistic by increasing the Great Barrier Reef protected area in recent decades from less than 5 per cent to 33 per cent. Due to the considerable uncertainties as regards scientific information, specific figures for coverage targets can only be temporary until better data and estimates become available.

Worldwide, significantly less than 1 per cent of the marine area is currently protected (Chape et al., 2005). In view of this fact, in addition to the need to establish a specific coverage target, there is considerable need for action, which is discussed in more detail in Section 2.6.2. As a basis for comparison: on land, around 12 per cent of land areas are protected (WPC, 2003b), which is much closer to the target coverage for ecosystem protection for terrestrial areas (10–20 per cent; WBGU, 2001). In terms of monitoring the implementation of coverage targets, the UNEP World Conservation Monitoring Centre and IUCN represent experienced and competent institutions that would be able to undertake monitoring activities if suitably equipped. There are also reporting obligations to be fulfilled, for example in the context of the Convention on Biological Diversity and the Ramsar Convention.

With coverage targets of this sort – as in the case of terrestrial areas – it cannot be emphasized too often that designation of protected areas is not sufficient in itself to ensure that protection actually takes place; good management and adequate funding are also prerequisites (WBGU, 2001). In addition, the remaining 70–80 per cent of the marine area not covered by protected area status must also be managed sustainably with integrated management concepts based on the ecosystem approach. Protected areas alone cannot stop the loss of biological diversity (WBGU, 2001), especially if overfishing is not halted and if there is a shift in climate zones. In the case of the ecosystems guard rail, moreover, the principle applies that adherence to the guard rail will only provide protection for marine ecosystems if the other guard rails too are implemented, especially the guard rails on climate protection (Box 1-1) and on ocean acidification (Section 4.4). Even the biggest and most proficiently managed protected areas system is only able to mitigate the consequences of unbridled climate change or extreme acidification to a very limited extent: the result would be an intolerable loss of ecological services over a large area.

2.6 Recommendations for action: Improving the management of marine ecosystems

Anthropogenic climate change has the potential to cause considerable additional stresses to marine ecosystems in future (Section 2.2–2.4). It is likewise possible that it will have an impact on commercial fishing, given that the naturally occurring variability in climate already plays a major role in the fluctuation of fish stocks. In some regions, anthropogenic temperature change is on the point of exceeding the highest levels ever reached by natural variability (e.g. in the Arctic: ACIA, 2005). Given the current state of knowledge, however, it is virtually impossible to make globally aggregated forecasts of the impact of climate change on marine ecosystems. As no comparable historical data or empirical figures are available, forecasts would amount to little more than speculation.

Mitigation of climate change, particularly by substantially reducing greenhouse gas emissions (WBGU, 2003; Schellnhuber et al., 2006), is crucial if additional stresses on marine ecosystems are to be limited. One mitigation option of direct relevance to oceans is sub-seabed storage of CO_2 (Chapter 5). Due to the geophysical lag effects of the climate system, however, adaptation measures will be unavoidable even if rigorous efforts are made to reduce emissions. For this reason, adaptation to climate change will be the focus of this section. Priorities set by WBGU in this context are fisheries management and marine protected areas. It makes sense to adopt adaptation measures for other reasons, too, as climate change is only one of many ways in which human influence degrades marine ecosystems (overfishing, destruction and pollution of marine ecosystems, invasion of alien species, etc.; GESAMP, 2001; UNEP, 2002). Even considered separately, each of these factors poses a considerable challenge to the international community.

Coupling and synergistic effects between the different factors call for particular attention (Brander, 2005). A coral reef that has suffered prior damage due to pirate fishing with poison or dynamite will be particularly sensitive to periods of unusually high temperatures (Section 3.3; Wilkinson, 2004). Where stocks of a species have been heavily depleted by overfishing, they will regenerate much more slowly if coastal ecosystems that serve as nursery grounds are exposed to severe stresses as a result of infrastructure measures or pollution, or if there is an additional stress in the form of warming. It is easy to find other examples to add to this list (for an overview, see Brander, 2005). Consequently, it is vital to consider the various factors in an integrated manner if management of marine ecosystems is to be successful. In the coming years, it will therefore become all the more important to rein in current overfishing practices and other destructive anthropogenic factors at the same time, so that marine ecosystems will have sufficient resilience to cope with climate change (Brander, 2005).

For these reasons, the ecosystem approach for promoting conservation and sustainable use of ecosystems and their living resources that was developed under the Convention on Biological Diversity and reaffirmed at the World Summit on Sustainable Development (WSSD) is vitally important (see e.g. OSPAR, 2003). In order to implement this approach, research and monitoring of marine ecosystems and ocean regimes must be improved and this knowledge applied to the assessment and management of fish species of commercial interest (FAO, 2003; Section 2.7). Current knowledge regarding the exceedingly complex interactions between climate, physical and chemical conditions in the sea, marine ecosystems and fishery is inadequate for making reliable predictions relating to how marine systems are likely to respond to climate change (ACIA, 2005; Section 2.7). Inadequate knowledge must not, however, serve as a pretext for delaying conservation and management measures. On the contrary: in accordance with the precautionary principle, action must be taken even if uncertainty prevails. This precautionary principle is already enshrined in multilateral fisheries policy, e.g., in the United Nations agreement on migratory fish stocks.

2.6.1 Fisheries management

National and international institutions face the challenge of dealing with the complex set of anthropogenic factors that currently characterizes the fisheries sector, of making decisions regarding sustainable management of the sector on this basis and, not least, implementing these decisions on the ground. Up to now, the situation has been less than satisfactory: calls for sustainable management of fish stocks, which we have been hearing for decades now and are reiterated time and again at international conferences, have hardly brought about any improvement in the overall situation (although there are some important regional exceptions) (Section 2.3). Half of all fish stocks are fully exploited, while a quarter of fish stocks have already collapsed as a result of overfishing (FAO, 2004). Illegal and unregulated fishing on the high seas continues to be an unresolved problem despite international efforts (FAO, 2001). In the future, this already very difficult situation will be exacerbated by climate change. In addition, new technologies have extended the boundaries of the feasible ever further in fishing, for example fish finding using much-improved sounding technology, and reaching great depths or particular stocks using modern catching methods. Nowadays, virtually no ocean habitat is inaccessible to fishing activities.

For these reasons, management of fishing grounds based on the ecosystem approach and on the precautionary principle is urgently needed in order to maintain the resilience of marine ecosystems (Scheffer et al., 2001; Pikitch et al., 2004). The Agreement on Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks in the high seas applies the precautionary principle. In FAO programmes, too (e.g. in the Code of Conduct for Responsible Fisheries; FAO, 1995), the precautionary principle and ecosystem conservation have played a major role for some time. The EU's strategy for protection of the marine environment names the ecosystem approach as a key component (EU Commission, 2005), although it excludes fisheries policy from this strategy. Moreover, the binding requirements it sets out are very vague, with the result that the strategy's effectiveness is likely to depend largely on how it is implemented by the Member States.

Broad-based enforcement of sustainable fisheries management is long overdue (Fujita et al., 2004). The scientific and conceptual foundations have already been laid and have been reaffirmed repeatedly in the international policy arena. In many cases legislative provision at national and regional level is already adequate. In the European Union, for example, the Common Fisheries Policy has been endowed with a legal framework that is perfectly acceptable in environmental policy terms. It has yet to be rigorously implemented, however, most notably implementation of adherence to the scientifically-based recommendations from the International Council for the Exploration of the Sea regarding catch quotas. Rapid elimination of excess fishing fleet capacity has also yet to take place (SRU, 2004). It is not the purpose of this section to discuss all the issues relating to global fisheries management and its shortcomings. The aim is rather to formulate recommendations or reinforce existing recommendations relating to the additional problem of climate change and its impact on fisheries.

- A paradigm shift away from publicly subsidized overfishing (SRU, 2004) to a sustainable fisheries sector is long overdue. In order to achieve this, efforts must be urgently intensified to resolve the primary problems of the marine fisheries sector, namely excess fishing fleet capacity, destructive fishing practices, excessive bycatch, inflated catch quotas, illegal or unregulated fishing in the high seas, habitat destruction in coastal ecosystems, and pollution. An increased drive to promote labelling of sustainable marine products is also urgently needed. Implementation of the goals adopted by the World Summit on Sustainable Development (WSSD) is a key yardstick in this context.
- Eliminating subsidies in the fisheries sector is an effective means of slowing overfishing and putting an end to it altogether in the long term. Estimates of subsidies to the fisheries sector worldwide range from US$15–30 thousand million annually (Milazzo, 1998; Virdin and Schorr, 2001). These subsidies should be cut in order to reduce incentives to overexploit the marine environment. At the same time, public funds would be set free for investment in activities that include protecting the marine environment.
- Recent efforts to reduce fisheries subsidies in the context of the WTO are welcomed by WBGU. This relates particularly to subsidies in the OECD countries and especially in the EU (SRU, 2004). The possibility of negative social and ecological consequences arising as a result of cuts in subsidies, particularly in developing countries, due to the search for new ways of earning an income or alternative ways of exploiting the natural environment, must be explored and, where appropriate, taken into account. This must not, however, be allowed to hold up implementation of a swift and consistent change in international policy on subsidies.
- Due to the complex interaction of many factors, both anthropogenic and natural, the integrated

ecosystem approach for promoting conservation and sustainable use of ecosystems and their living resources developed under the Convention on Biological Diversity and reaffirmed at the WSSD is vitally important. On the one hand, monitoring of ocean regimes and ecosystem parameters (e.g. indicator species) must be improved; on the other, the resulting knowledge concerning the state of the ecosystem must be integrated into the process of assessing and managing commercially important fish stocks (FAO, 2003).

- The precautionary principle must be rigorously applied as the basis for fisheries management. Particularly when forecasting fish stock dynamics and calculating catch quotas on the basis of these, safety margins should be included to ensure that stocks do not fall below the minimum required for reproduction and that the age structure of the fish population remains healthy, even in the event of a regime shift induced by climate change (King, 2005). Fisheries management must be enabled to respond to regime shifts in good time and with appropriate strategies (Polovina, 2005). One example of the need to adapt in this way is the cod fishery in the North Sea (Section 2.3.1).
- For short-term management (1–5 years), although anthropogenic climate change will have relatively little impact, interannual variability and climatic events such as El Niño may trigger major effects (Barber, 2001). Assessing and forecasting these factors is an important area where research is needed.
- The role of the future climate is currently largely ignored when developing management strategies for the medium term (5–25 years), either because it is seen as something that can be disregarded or because it is considered impossible to foresee. Since climate change can have considerable impact on recruitment and distribution of fish stocks in the medium term, it will become necessary for fisheries management to take these effects into consideration. At present, the impact of climate variability and climatic events on fish stocks can only be analysed after the event. In view of the fact that climate change is already apparent, forecasting capacity needs to be developed in future and used to conduct risk analyses. This applies particularly to sensitive fish populations on the edge of their natural distribution area.
- When developing the models that are used as the basis for setting quotas, there needs to be a shift away from analysing and modelling individual fish populations of commercial interest to ecosystem-based models that take into account the dynamic interactions between climate, ocean and marine ecosystems (Pikitch et al., 2004). The usefulness of static concepts based on the assumption of unchanging environmental conditions is becoming increasingly questionable.
- In the case of terrestrial ecosystems, subdividing the area in question into zones with varying intensities of use is a long-established procedure for solving land-use conflicts (WBGU, 2001). For the oceans too, in the context of marine spatial planning systems, zoning is increasingly recognized as a useful instrument for sustainable, ecosystem-based fisheries management (Pauly et al., 2002; SRU, 2004; Pikitch et al., 2004; Boersma et al., 2004). Marine protected areas have a special role to play as a component of marine spatial planning in this context because, in conjunction with other measures, they represent an important tool for implementing the ecosystem approach. Recommendations relating to this are discussed in more detail in the next Section 2.6.2.

2.6.2 Marine protected areas

2.6.2.1 Definition and motivation

Climate change, ocean acidification and sea-level rise will have considerable impact on the marine environment (Sections 2.2–2.4). These 'new' anthropogenic factors, moreover, are affecting marine ecosystems which, in many regions, have already been significantly weakened by overfishing, contamination, invasive species and other human-induced influences. Recommendations for improving fisheries management were presented in Section 2.6.1 above. This section will deal with marine protected areas (MPAs), which – like their counterparts on land – are one of the most important instruments available for ecosystem protection (IUCN, 1994; Kelleher, 1999; Murray et al., 1999).

IUCN defines marine protected areas as 'any area of the intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment' (IUCN, 1988).

MPAs play a particular role in protecting the marine environment, as they are a direct means of implementing the ecosystem approach, and one of the easiest to apply (Royal Commission on Environmental Pollution, 2004). Although they cannot halt either climate change or acidification, nor altogether prevent invasion by alien or highly migratory species, they are an important tool for enhancing the resilience and adaptive capacity of ecosystems. They are also important because they allow mitigation of anthropogenic factors such as overfishing or habitat destruction within their boundaries by means of management or prohibition (e.g. Mumby et al., 2006). MPAs are thus the most important means, for example, of dealing with coral bleaching (Section 3.3.4), because although they do not tackle the underlying cause, they can enhance the general resilience of the reef (Grimsditch and Salm, 2005). However, enhanced scientific understanding of the relationship between resilience, anthropogenic influence and biological diversity is needed (Section 2.7). For coastal protection, near-natural ecosystems are also important: for example, the Asian tsunami of 26 December 2004 was able to penetrate much further inland in places where the mangroves or coral reefs had been destroyed than elsewhere (Danielsen et al., 2005; Fernando and McCulley, 2005). Protected coastal ecosystems are therefore also an important component of strategies for adapting to climate change (Section 3.4.1).

In addition to their role in ecosystem protection, MPAs can also be useful as a fishery management tool for conservation of commercial fish stocks, e.g. where traditional management has failed and overfishing has resulted, or to safeguard against future mistakes of this sort (Bohnsack, 1998; Pauly, et al., 2002; Gell and Roberts, 2003). Even conservation-based fishery can have a range of negative effects on marine ecosystems, and establishing MPAs can mitigate these (Palumbi, 2003). MPAs can also provide a retreat for species that are fished, but are not subject to monitoring or management. Coastal ecosystems and estuaries are also important for protecting the nursery grounds of many fish species against climate variability (Attrill and Power, 2002). MPAs should be viewed in conjunction with the traditional tools of fishery management, for one reason because quota setting could also be affected by the establishment of a large-scale network of MPAs if fishery activities are restricted to the areas outside MPAs (Hilborn, 2003).

A graded system of protected area management categories is applied in the marine environment too. This ranges from total protection (marine reserves where extractive use is prohibited) to areas serving primarily to uphold sustainable and/or traditional use of marine resources (IUCN, 1994). Areas that are closed to fishing activities (no-take areas) represent a special type of MPA. Different categories of protected area often sit side by side, with core areas under strict protection and peripheral zones with fewer restrictions relating to use (Agardy et al., 2003). The effectiveness of MPAs can be improved if they form part of a protected areas system geared towards ensuring ecological representativeness and creating networks.

Although differences of opinion still persist with regard to the optimum design and management of marine protected areas (NRC, 2001), there is broad consensus that adaptive management, linking of individual MPAs to protected areas systems, participation or co-management and an integrated view of the relationship between MPAs and the intensively exploited areas outside them are important aspects of MPA design and management.

2.6.2.2 International policy objectives

Because of the double use of MPAs for ecosystem conservation on the one hand and as a fishery management tool on the other (Lubchenko et al., 2003), as a guard rail, WBGU recommends designating 20–30 per cent of the marine area for inclusion in a linked system of MPAs (Section 2.5.1). Current protected areas coverage amounts to less than 1 per cent of marine habitats. Considerable catching up is therefore required and it is only very recently that this has led to the formulation of a number of policy objectives in this area:

- At the WSSD, the international community set itself the target of establishing an ecologically representative and effectively managed network of marine protected areas by 2012 (WSSD, 2002).
- The World Parks Congress reaffirmed this goal in 2003 and made it more specific with the recommendation that at least 20–30 per cent of every marine habitat should be strictly protected (WPC, 2003a).
- In the context of its programme of work on protected areas, the Convention on Biological Diversity has adopted the WSSD target for protected areas, albeit without specifying a coverage percentage (CBD, 2004a).
- A regional example is the OSPAR/HELCOM Convention, which has also set itself the target of creating a well managed and ecologically coherent system of marine protected areas by the year 2010 (OSPAR, 2003).

2.6.2.3 Present international law

Although the concept of MPAs or related strategies are used in the different international conventions, they are not used consistently and thus need to be expressed in more concrete terms (Agardy et al., 2003). Policy objectives are set out in the following provisions of international law:

- The Convention on Biological Diversity – whose objectives also cover marine ecosystems – envisages protected areas as an *in situ* conservation measure (Art. 8 a).
- The United Nations Convention on the Law of the Sea (UNCLOS) makes explicit mention of special protected areas only in the following context: Art. 211, para. 6 allows tightening of protective regulations in clearly defined areas in connection with measures to prevent pollution of the marine environment from vessels. Coastal states wishing to apply this provision can designate such an area within their respective exclusive economic zone, and apply to the competent international organization, the International Maritime Organization (IMO), requesting affirmation of the need for special measures to protect this area. Reasons may be related to the area's oceanographical and ecological conditions, its utilization or protection of its resources. Under this provision, however, special measures are restricted to regulations for the prevention of pollution from vessels.
- In various agreements in the field of international law on protection of the marine environment, there are terms and concepts that have similar objectives to MPAs. The International Convention for the Prevention of Pollution from Ships (MARPOL Convention), for example, provides for the establishment of 'Particularly Sensitive Sea Areas' (PSSAs). The purpose of the protected areas in this case is to ensure protection from pollution from ships in particularly vulnerable areas that are to be designated accordingly. Further examples are the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) and the Convention for the Protection of the Mediterranean Sea against Pollution (Barcelona Convention), both of which have a specific additional annex (OSPAR) or protocol (Barcelona Convention) on the establishment of 'Specially Protected Areas'. IMO has adopted a Resolution (A.885 (21)) setting out procedures for the establishment of PSSAs (Hohmann, 2001).

Requirements for designating protected areas vary according to the maritime area in question. The limits set out under international law depend primarily on the maritime area in which the protected area is to be established in a given case (Box 2.6-1; Proelß, 2004).

- In principle, in the case of internal waters and territorial sea, the coastal state has the freedom to decide on designation of MPAs. This may be limited to a certain extent, but only with regard to restrictions on shipping activities (Box 2.6-1).
- The legal situation with regard to exclusive economic zones (EEZ) is similar. UNCLOS accords particular sovereign rights to coastal states in this maritime area concerning exploitation and conservation of the living and non-living natural resources in the maritime area in question, including the seabed and its subsoil. In relation to establishing MPAs, this means that the coastal state has the freedom to adopt measures so long as these measures are aimed at restricting exploitation of natural resources. However, the establishment of an MPA in this area may not, for example, restrict the right of innocent passage of foreign vessels (Box 2.6-1).
- On the high seas, although the establishment of MPAs is not ruled out in principle (Proelß, 2004), it entails certain legal problems (Platzöder 2001; Warner 2001). These are discussed in Section 2.6.2.4.
- In contrast to agreements that are limited to particular regions (e.g. the OSPAR Convention, the Convention for the Protection of the Marine Environment of the Baltic Sea – the Helsinki Convention, or the Barcelona Convention) there is currently no global instrument of international law that specially promotes designation of cross-border MPAs or places any obligation on states to do so.

2.6.2.4 Marine protected areas in the high seas

There are significant deficits in the legislation pertaining to establishment of marine protected areas in the high seas (CBD, 2005a). The regional multi-functional maritime conventions only cover a very limited range of marine areas outside national jurisdiction, with the result that large areas of the world's oceans are not covered. In addition, existing regional fishery management regimes are limited to particular fished species such as tuna, while species that are not intensively fished are excluded. Application of the ecosystem approach under these regimes is also inadequate.

The United Nations Convention on the Law of the Sea (UNCLOS) reaffirms the right to freedom of navigation, which forms part of customary international law (i.e. it is a right that, in principle, cannot be restricted) (Art. 87 UNCLOS). It is thus out of the question to establish an MPA in the high seas that entails the prohibition or restriction of shipping activities. In addition, states may not conclude agreements establishing MPAs in the high seas that might

Box 2.6-1

Maritime zones under international law

The United Nations Convention on the Law of the Sea (UNCLOS) lays down the fundamental provisions under international law with respect to delimitation of maritime zones, and this is also relevant for designation of MPAs. In brief, the maritime zones under UNCLOS are organized as follows (Figure 2.6-1):

- *High seas:* According to Articles 86 and 89 UNCLOS, 'high seas' are those parts of the sea that are not subject to the sovereignty or jurisdiction of any state and as such constitute 'an area under international administration'. The principle of freedom of the high seas applies in this area. This comprises primarily freedom of navigation and of overflight, freedom to lay submarine cables and pipelines, freedom to construct artificial islands and other installations, freedom of fishing and freedom of scientific research. These freedoms may be exercised by all states, including land-locked states. In the area constituting the high seas, no state may validly purport to impose restrictions of any sort on other states relating to use of the high seas. Furthermore, international agreements between individual states can always only bind the states that are party to the agreement, and not third states.

A distinction is drawn between the high seas and maritime areas that are subject to varying degrees of territorial jurisdiction by the coastal state. According to Article 86 UNCLOS, the maritime areas over which the coastal state has varying degrees of jurisdiction are:

- *Exclusive economic zone:* Here, in the zone that lies on the boundary with the high seas, the coastal state begins to have the right to exercise jurisdiction based on its territorial rights. The corresponding rights of sovereignty, however, are limited insofar as they relate exclusively to exploitation and conservation of the living and non-living natural resources in the zone in question, including those in the seabed and its subsoil.
- *Continental shelf:* This term too is defined in terms of the right to exploit natural resources, although in this case it is specifically those of the seabed and subsoil close to the coast. Thus, according to Article 77 para. 1 and 2 UNCLOS, the coastal state exercises over the continental shelf exclusive sovereign rights for the purpose of exploring it and exploiting its natural resources. The definition of resources that applies in the case of exploitation of the continental shelf, however, is somewhat restricted by comparison with that of the exclusive economic zone (non-living resources of the seabed and its subsoil and 'immobile' organisms).
- *Territorial sea:* Here, the special rights of coastal states are no longer limited to exploitation of marine resources, but are identical to actual territorial sovereignty.
- *Internal waters:* This is where the sovereign rights and jurisdiction of a coastal state are most extensive; this maritime zone forms an integral part of a state's territory.

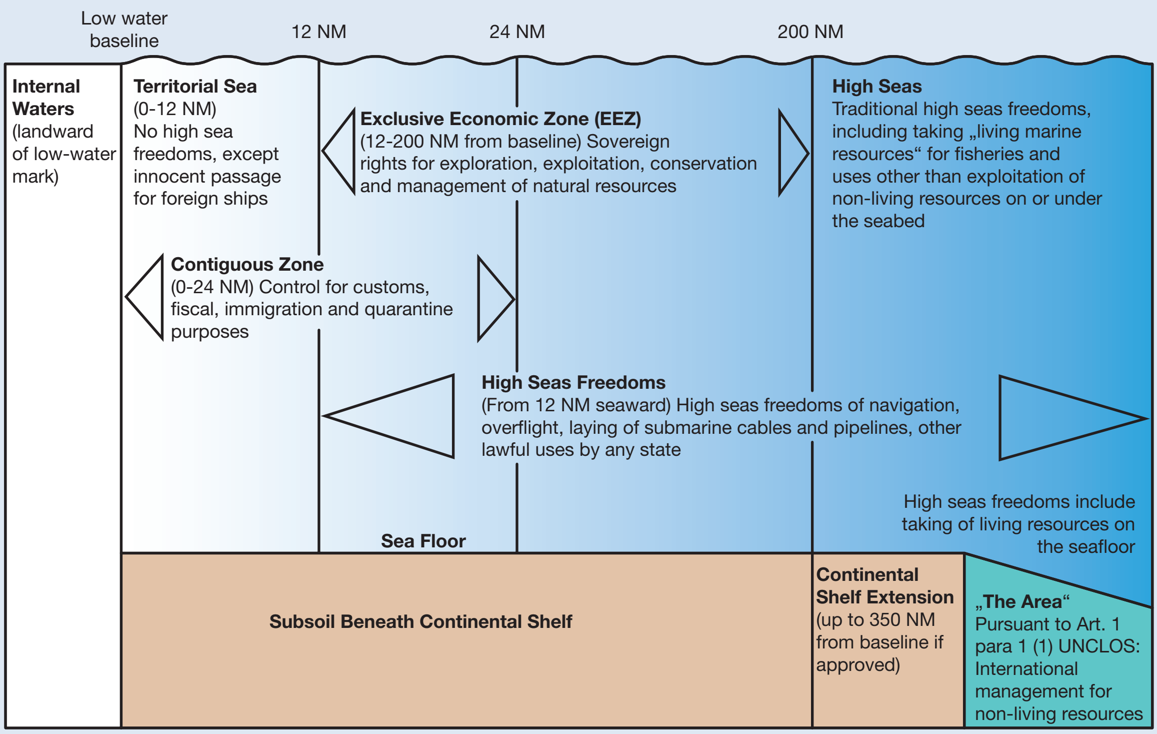


Figure 2.6-1
Maritime zones under the United Nations Convention on the Law of the Sea (UNCLOS). NM = nautical mile (1 NM = 1.852 km).
Source: Gorina-Ysern et al., 2004

be detrimental to third states that are not parties to the agreement. A corresponding commitment agreement among states in a particular region that are the main users of the high seas thus has no binding effect on third states. 'Freedom of the high seas' also includes, for example, the fundamental right of every state to use the marine resources of the high seas (e.g. fishing). In contrast to the case of freedom of navigation, however, this right is not unrestricted, and correspondingly there is a range of international conventions regulating the use of living marine resources in the high seas, especially relating to particular species. Examples include the prohibition on fishing of anadromous species (e.g. salmon, which spawns in freshwater but lives in seawater) in the high seas in accordance with Art. 66, para. 3(a) UNCLOS, or the whale sanctuaries provided for under the International Convention for the Regulation of Whaling (Gerber et al., 2005).

Urgent problems such as the increasing destruction due to fishery activities of sensitive undersea structures that are particularly rich in biological diversity (e.g. seamounts or cold-water coral reefs; UNGA, 2004; CBD, 2004b), and the scale of illegal and unregulated fishing (FAO, 2001), necessitate rapid identification and implementation of solutions for marine protection in the high seas. In view of the clear will of the international community to step up use of marine protected areas as a tool, action is needed to improve provisions pertaining to MPAs in the high seas under international law. In developing a regime for marine protected areas in the high seas, the following specific requirements should be met (CBD, 2005a):

- Moving beyond approaches that focus on specific species or regions, the aim should be to arrive at an integrated approach enabling the creation of large-scale networks for protecting marine ecosystems in the high seas too. Freedom of access to marine protected areas in the high seas should also be guaranteed for scientific research, insofar as this does not run counter to conservation objectives.
- In view of the problem of illegal and unregulated fishing in the high seas – which cannot be tackled by individual states because they do not have territorial jurisdiction to enforce the law in this maritime zone – mechanisms for enforcing the relevant conservation requirements in the high seas must be considered (Platzöder, 2001; Warner, 2001).
- In view of the need to create networks that cover a broad area, efforts should be made to ensure that the establishment of MPAs in the high seas – contrary to what has happened hitherto under the various specific conventions – takes place in a coordinated fashion (CBD, 2005b).

2.6.2.5 Negotiation processes

At global level, negotiations on MPAs are taking place notably in two parallel political processes:

- In the Convention on Biological Diversity, MPAs are on the agenda of a Working Group on Protected Areas, including protected areas beyond the limits of national jurisdiction. However, attempts to agree specific areas of the high seas that might be suitable for designation as MPAs or set a specific target of establishing 5–10 MPAs in the high seas by 2008 have so far failed due to resistance on the part of a few fishing nations (e.g. Iceland, Norway, New Zealand).
- In 2004 an informal Working Group of the General Assembly of the United Nations was established (UNGA, 2004) with a broad mandate relating to marine biodiversity conservation beyond areas of national jurisdiction. This Working Group convened for the first time in February 2006. Although the positions of the different country groups on MPAs still diverge widely, many states acknowledge the need to act to close this gap in international law.

2.6.2.6 Recommendations for action relating to marine protected areas

Despite the importance of marine protected areas, protection of the marine environment must not be reduced to this one instrument alone. Adherence to the ecological guard rail (20–30 per cent of marine ecosystem areas under protection; Section 2.5) is indispensable for conservation of the marine environment, but areas outside MPAs must also be managed sustainably using the ecosystem approach. A particularly important precondition for the success of MPAs is the urgently needed enforcement of sustainable fisheries management (Section 2.6.1). Another precondition is adherence to the guard rails on climate change and ocean acidification (Box 7-1), without which even an excellent protected areas system will lose most of its impact. In addition, it is not sufficient to plan, designate and link MPAs; they must also be well managed and adequately funded. Only in this way is there a chance that the target of significantly reducing the rate of loss of biological diversity by 2010 can be met in marine environments too.

Implementing international targets

- The rate of growth of MPA coverage, currently 3–5 per cent per year, is much too low to meet the internationally agreed targets on time, given that current coverage is less than one per cent (Wood et al., 2005). Efforts in this regard need to be intensified significantly.
- MPAs should be sufficiently large and linked with one another in protected area systems; they should encompass zones with different forms and intensities of use and be part of an integrated system of management that includes neighbouring continental shelf and coastal areas. In addition, they should be designed to be flexible and adaptive, since climate change may impose the need for reorganization if ecosystem processes change or shift in location (Soto, 2002). Improving the scientific basis in this context should be carried out in parallel with ongoing management activities. Adaptive management strategies and flexibility are crucial to deal with local impacts of climate change that are difficult to forecast.
- In the territorial sea and in EEZs, states can begin to implement international objectives now without coming up against problems relating to international law. The EU Habitats Directive and Birds Directive are both fully applicable in EEZs. In Germany this has already taken place: in the context of the Natura 2000 network, around 30 per cent of the German maritime area of the EEZ has been registered as protected areas with the European Commission. However, imposing restrictions on fishing is not a straightforward matter at present, as this is an area in which EU competences apply. MPAs should be used more effectively as a tool for sustainable fisheries, for example by setting long-term or temporary limits on fishing activities in protected areas (SRU, 2004).
- In developing countries particularly, there is a great deal of catching up to be done. In these countries, not only are there very few MPAs, but the designated protected areas in many cases amount to little more than 'paper parks' in which effective protection is not or cannot be enforced. Development cooperation should therefore make designation and management of MPAs a priority. In doing so, cooperation should take place between protected areas specialists and fishery representatives, and the local population should be involved in planning and management.

Securing funding

Due to the difference between the guard rail for protection of marine ecosystems (20–30 per cent coverage) and current coverage (less than 1 per cent of marine ecosystems are currently protected; Section 2.5.2), the need for additional funding is considerable. According to the findings of Balmford et al. (2004), the annual costs associated with protecting marine ecosystems on this scale would be in the region of US$5–19 thousand million. This figure includes both ongoing costs and one-off costs relating to implementation. Indirect costs, however, such as costs to businesses in the fisheries sector arising as a result of fishing exclusion, are not included.

- WBGU considers it to be the responsibility of national governments and the international donor community to ensure adequate funding for management of marine protected areas. Up to now, it has often proved impossible to ensure availability of adequate long-term financing: payments from public donors are often small and there are competing demands on these resources. The same applies to international transfer payments such as those made by the Global Environment Facility (GEF) or by donors in the context of bilateral development cooperation (OECD, 2002; GEF, 2005a). WBGU calls upon public donors to undertake additional efforts to make adequate funding available on a sustained basis. Complementary funding may be raised by means of instruments such as user charges or promoting private donations for conservation measures (Emerton, 1999; Morling, 2004).

Protected areas in the high seas: Closing gaps in international law

The ongoing process of political negotiations to develop an instrument for designating and managing protected areas in the high seas is to be welcomed, and the German Federal Government should give this process vigorous support. The basis for this is UNCLOS. Despite the fact that UNCLOS lays greater emphasis on rules pertaining to usage than on protection and conservation of marine resources, it nevertheless also provides the primary legal framework for protection of the marine environment (Platzöder, 2001). Fundamentally changing UNCLOS is not a political option, whereas adding moderate supplementary provisions to the current law of the sea seems feasible in both political and legislative terms. Options for doing this include the following:

- The primary task is to develop a multilateral agreement on designation of protected areas and corresponding systems in the high seas and append this to UNCLOS, either as an additional protocol or as a supplementary convention. A precedent already exists for this type of procedure in the form of the Agreement relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks that is tied to UNCLOS, and which is concerned primarily with the exploitation of relevant fish species in areas outside national jusrisdiction.

- It would make sense to assign the monitoring and coordination tasks to the same – yet to be established – international regime. From a legal perspective, the mechanism should be laid down primarily in the above-mentioned multilateral agreement. With regard to this, the proposal to establish a Global Oceans Commission, put forward at the first International Marine Protected Areas Congress in 2005 in Geelong (Australia), can be considered as being along the right lines.
- The Convention on Biological Diversity (CBD) should also be amended or supplemented accordingly, whereby care will need to be taken to avoid overlap. The CBD has developed considerable expertise in the field of biodiversity conservation, and should therefore be involved in the UNCLOS negotiation process, for example by providing expert input. At the same time, the new regime's functions and areas of responsibility should be explicitly recognized by the CBD. In order to achieve this, the relevant CBD negotiation processes should be intensified with the aim of securing a key role for the CBD in the design of MPAs in the high seas in terms of content, e.g. deciding on appropriate instruments and criteria for the selection of MPAs. With a view to supporting cross-border conservation efforts, it would be useful to explore whether it would be worthwhile developing a protocol to the CBD on protected areas in the medium term based on the findings of the current Working Group. Such a protocol should cover the whole spectrum of protected areas and not merely MPAs.
- The informal Working Group of the General Assembly of the United Nations on marine biodiversity in areas beyond national jurisdiction has taken the first step towards closing the gap in international law regarding MPAs in the high seas. At the next UN General Assembly, the German Federal Government should urge that this sound basis be used to ensure continuation of the negotiation process.

2.7 Research recommendations

Research into climatic factors

- *Behaviour of sea ice:* Possibilities for monitoring changes in the thickness of Arctic sea ice in particular remain inadequate, and sea ice simulation models need to be developed further in order to improve estimation of future sea ice dynamics.
- *Behaviour of continental ice:* The future behaviour of Greenland's continental ice sheet is likely to be decisive for the future dynamics of ocean currents in the Atlantic. Methods of modelling continental ice sheet dynamics need to be improved significantly.
- *Stability of Atlantic circulation and risks of changes in currents:* Climate models continue to differ considerably as regards the information they provide on the future stability of ocean currents. Reasons for this include internal oceanic processes (such as mixing), which as yet are poorly understood, and interactions with other climate components (e.g. the freshwater budget of the North Atlantic), which are difficult to quantify. Observation and enhanced modelling efforts could help to reduce the uncertainties in this area.

Research into marine ecosystems, fisheries and marine protected areas

- *Monitoring:* Observation data covering large areas of the oceans over long periods are vital, particularly as regards the nutrient situation and plankton (especially zooplankton). Because they provide, among other things, important inputs for modelling marine ecosystems, support should be given to appropriate monitoring programmes (e.g. using the Continuous Plankton Recorder).
- *Understanding the systems involved:* Too little is known about the structure and dynamics of marine ecosystems to be able to make reliable estimates of the impact of climate change. Examples include the significance of temperature effects on primary production, the impact of sea-ice retreat, or decoupling of trophic levels as a result of disparities in species' responses to climate change (e.g. migration, adaptation). Increased emphasis should be given to ecosystem-based research approaches with a view to enhancing understanding of the relationships between anthropogenic disturbance, biological diversity and resilience of marine ecosystems and incorporating this into new ecosystem models. The international research project GLOBEC and the new IMBER project have drawn up a detailed catalogue of issues (GLOBEC, 1999; IMBER, 2005). Promotion of these interdisciplinary research initiatives by national research promotion agencies should be stepped up.
- *Modelling marine ecosystems:* In order to gain a better understanding of the impact of changes in climatic factors (temperature, wind and ocean current patterns, etc.) on marine ecosystems, knowledge regarding the various ecosystem components must be integrated into improved ecosystem models and coupled with recent climate/ocean models.

- *Improving the basis of fisheries management:* In order to implement the ecosystem approach in fisheries management, there needs to be a shift in focus in terms of model development away from examination of individual fish species under the assumption of constant environmental conditions to a more integrated ecosystem modelling approach. Qualitative models should also be used to achieve this, incorporating expert knowledge regarding processes in dynamic systems (Kropp et al., 2005). Special attention should be paid to the impact of natural climatic variability and anthropogenic climate change on fish population dynamics, as well as to the socio-economic consequences and possible adaptation measures.
- *Design and management of marine protected areas:* Development of the theoretical basis for the design of marine protected areas should move away from the study of individual species towards multi-species, ecosystem approaches. Of particular importance in this context is the networking of MPAs with one another and with concepts for sustainable use of the surrounding coastal and marine areas. There are many unanswered questions regarding the design of MPAs in view of climate change and the potential for adaptation. In line with the principle of adaptive management, research and monitoring issues need to be given greater consideration in the design and management of MPAs. The basis for defining guard rails and coverage targets needs to be improved, particularly the basis for designating the proportion of an area that should be strictly protected (no-take areas). Furthermore, there is a need to increase research evaluating participatory approaches (e.g. community-based management) and the use of traditional knowledge, and to evaluate approaches that draw on management experience within the local population.

3.1 Climatic factors

3.1.1 Sea-level rise

3.1.1.1 Lessons from Earth's history

A rise in sea level is one of the unavoidable physical consequences of global warming. A close link between temperature and sea level is also evident in climate history. At the peak of the last ice age (around 20,000 years ago) sea level was around 120m lower than today, and the climate was about 4–7 °C colder. By contrast, during the last warm period, the Eem (120,000 years ago), the climate was slightly warmer than today (by approx. 1 °C), but sea level was probably several metres higher – estimates vary from 2 to 6m (Oppenheimer and Alley, 2004). Going back farther into the Earth's history, one can find even warmer climate epochs. Three million years ago, during the Pliocene, the average climate was about 2–3 °C warmer than today and sea level was 25–35m higher (Dowsett et al., 1994).

The main reason for these large sea-level changes is the change in quantities of water that are tied up on the land in the form of ice. The 'sea-level equivalent' of the ice mass on Greenland equates to 7m, the West Antarctic ice sheet to 6m, and the East Antarctic ice sheet to more than 50m. Around 35 million years ago (in the Eocene) was the last time our planet was completely free of polar ice caps, thanks to high CO_2 concentrations related to the plate-tectonic situation at the time, and sea level was almost 70m higher than today (Zachos et al., 2001; Barrett, 2003). In this kind of time frame, however, volume changes in the ocean basins due to plate tectonics can also contribute to sea-level changes.

Plotting the values above on a graph (Fig. 3.1-1) reveals a relationship between temperature and sea level, where a global warming of 3 °C corresponds to a sea-level rise of several tens of metres. This is an order of magnitude more than the IPCC expects by the year 2100 (9–88cm; IPCC, 2001a). The main reason for this apparent discrepancy is that the relationship shown in the figure is based on a climate near equilibrium (following many millennia with relatively constant temperatures) – not during rapid changes as they are now occurring. The numbers give a general idea of how sea level would change after millennia with a 3 °C warming. But they do not allow any conclusions about how fast the ice masses could melt with warming and how quickly sea level could rise in response.

The end of the last ice age provides information about the possible rate of sea-level rise. At that time the global average temperature rose by around 4–7 °C, an amount that is also reached in pessimistic scenarios for the future. But the warming at that time took around 5000 years, which is much slower than the present trend. From 15,000 to 10,000 years ago sea level rose by around 80m, an average of 1.6m per century (Fairbanks, 1989). During some intervals

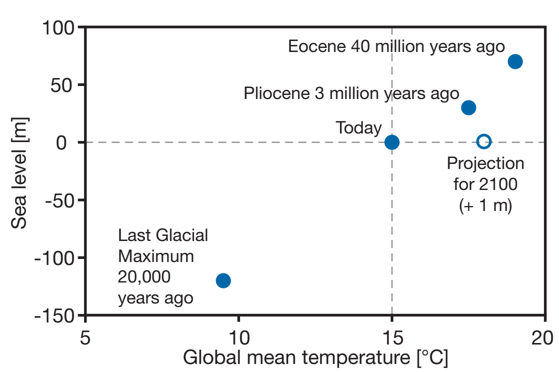


Figure 3.1-1
Mean global temperature and sea level (relative to today's) at different times in Earth's history, with the projection for the year 2100 (1m above today's sea level). For the long term a much higher sea-level rise probably has to be assumed than that predicted for 2100.
Source: after Archer, 2006

rates of up to 5m per century were reached (Clark et al., 2004).

These values cannot simply be applied to today's situation. The ice sheets at that time were considerably larger, which means the melting regions on the margins were greater, allowing a greater flow of meltwater. In addition, due to Earth's orbital cycles around the sun (Milankovich cycles; Ruddiman, 2000), the incoming solar radiation at high latitudes of the Northern Hemisphere was considerably stronger, a situation that cannot be directly compared with the global increase in greenhouse gas concentrations. These two factors suggest higher melting rates at the end of the ice age than during the present warming. The much slower warming at that time, by contrast, would suggest lower melting rates. In fact, the disappearance of ice sheets at that time for the most part kept pace with the gradual climate warming, so the assumption that ice masses would have melted significantly more rapidly with faster warming is quite plausible.

Two conclusions can be drawn from this discussion. Firstly, rates for sea-level rise of up to 5m per century are documented, and these probably do not represent an upper limit. Thus climate history shows that a much more rapid rise than that expected by the IPCC for the 21st century is possible. Secondly, such rates of sea-level rise suggest dynamic melting processes of the ice sheets, also taking account of the conditions at the end of the last ice age. This means there can be not only a simple melting through contact with warmer air, but also an accelerated flow of the ice into the sea.

3.1.1.2 Dynamics of the continental ice masses

The Earth presently has two large continental ice sheets with a thickness of 3–4km, in Greenland and Antarctica. Both are in a steady-state: in the centre new ice is continuously formed by snowfall, while ice flows away on the margins. Under persistently constant climatic conditions these processes are in balance and the size of the ice mass does not change. But in the Antarctic it is significantly colder than in Greenland. In Greenland, therefore, a large part of the ice at the margins melts while still on the land (like on a mountain glacier), while in the Antarctic it reaches the sea and tongues of the ice float on the water to form ice shelves.

It is still difficult to reliably measure changes in the total volume of these two ice masses. Efforts include elevation profiles taken from satellites and aeroplanes. There is still controversy over the margin of error of these measurements; they do not accurately record the craggy topography often found on the margins of the ice sheets. Newer techniques include satellite measurements of anomalies in the gravitational field. Changes at the margins of the ice masses are best obtained by local measurements and determination of the flow rate of the ice by satellites.

The various measurement methods provide the following qualitative picture for both ice sheets: in the past ten to twenty years, the thickness in the centre seems to be increasing somewhat, as should be expected with climate warming because of increased snowfall. On the other hand, increasing dynamic melting processes can be observed on the margins. The quantitative net balance of these processes is not exactly known, so a short discussion of the current measurement results follows.

In Greenland around half of the ice flows out of only 12 fast-moving outlet glaciers; the mass balance of the ice depends largely on changes in these ice flows (Dowdeswell, 2006). New data show that the flow rates of many of these glaciers (among others the Jakobshavn Isbrae) have doubled in recent years (Joughin et al., 2004; Rignot and Kanagaratnam, 2006). Furthermore, measurements of the melt area, which can be determined from satellite pictures, show an increase of around 25 per cent from 1979 to 2005 (Fig. 3.1-2); the area reached its highest extent ever in the year 2005 (Steffen and Huff, 2005). When the area that is affected by melting increases, it should cause a loss of mass in the ice cap. It has also been found that meltwater from the ice surface runs through holes (so-called glacier mills) to the base of the ice and acts like a lubricant there, accelerating the flow of the ice (Zwally et al., 2002).

Rignot and Kanagaratnam (2006) conclude that the acceleration of the ice flow represents a loss of mass corresponding to 0.5mm of sea-level rise per year, and that this value has doubled in the past ten years. This is equal to one-sixth of the current measured global sea-level rise (Fig. 3.1-4). This is in contrast to measurements of the elevation of the ice by satellite altimeters (Johanessen et al., 2005; Zwally et al., 2005), which indicate an increase in the mass of the Greenland ice (corresponding to a sea-level change of -0.03mm per year), but which do not accurately register the small-scale processes at the margins. Because this increase is significantly smaller than the loss observed by Rignot and Kanagaratnam, a net mass loss of Greenland ice has to be assumed, although there are considerable uncertainties in the numbers, and the various measurement methods yet need to be better reconciled.

More important, however, than the present changes in mass balance, which are still small and impossible to record accurately, is what is to be expected in the future with progressive warming.

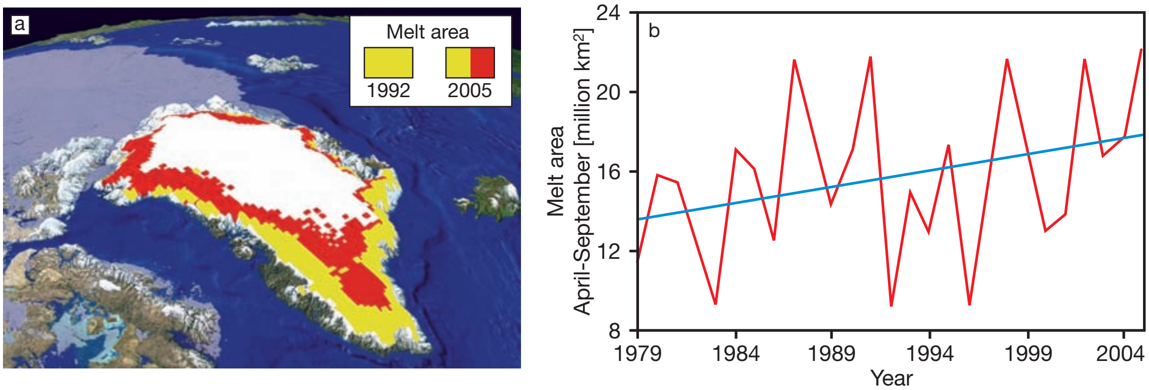


Figure 3.1-2
Extent of melt area on Greenland according to satellite data. The two extreme years 1992 (after the eruption of Pinatubo) and 2005 are shown (a), and the development over time (b).
Source: Steffen and Huff, 2005

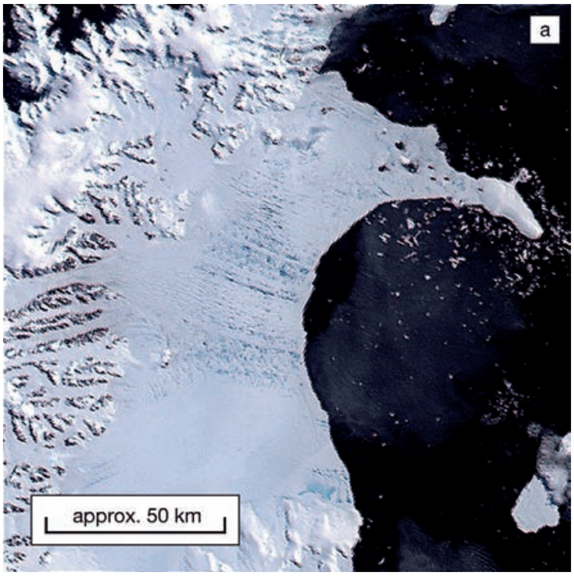
Model calculations show that with a warming of the near-surface air layer above Greenland of about 2.7 °C or more, it is likely that the entire ice sheet will gradually melt (Gregory et al., 2004). Chylek and Lohmann (2005) estimate that the warming over Greenland is 2.2 times the global warming (a result of climate change feedbacks near the poles), so that the critical warming over Greenland could be reached with a global warming of only 1.2 °C.

The rate at which Greenland ice could melt – and therefore sea level could rise – is still an open question. The last IPCC report assumed a relatively simple model with conservative estimates using the difference between melting and snowfall, and concluded a duration for melting of several millennia (IPCC, 2001a). But that report did not consider the dynamic flow processes discussed above, which have since been observed and could imply a much faster reduction of the ice. This process is not taken fully into account in present ice models.

For the Antarctic ice masses the 2001 IPCC report predicted no melting, but, in contrast, a slight growth of ice due to increased amounts of snowfall. New data, however, also indicate a mass loss in the Antarctic and a dynamic response of the ice, especially in the smaller West Antarctic ice sheet. In February 2002 there was a spectacular collapse of the millennia-old Larsen B ice shelf off the Antarctic peninsula after warming in this region (Fig. 3.1-3). This has no direct effect on sea level, because ice shelves float on the sea and their mass displaces a corresponding amount of water. But it evidently has effects on the continental ice: the ice flows behind the Larsen B ice shelf which flow down from the continent have strongly accelerated since then (to up to eight times the speed: Rignot et al., 2004; Scambos et al., 2004). The floating ice shelves hang in part on projecting rocks, hence impede the flow of the ice into the sea. The flow of continental ice has also accelerated in other areas of the Antarctic, for example, in Pine Island Bay (Rignot et al., 2002). In addition, it has been shown that the melting rate of the ice flow where it reaches the sea is very sensitive to the sea temperatures: per 0.1 °C rise in the water temperature the melting rate increases by one metre per year (Rignot and Jacobs, 2002). Thus, if the water temperatures around the Antarctic increase or if large ice shelves like the Ross Ice Shelf should one day disappear, then one has to assume that there will be a corresponding acceleration of the flow of the West Antarctic ice sheet.

Latest data from the GRACE satellite, which can precisely measure anomalies in the gravitational field, indicate a shrinking of the Antarctic ice masses by 152 km^3 per year over recent years. This equates to a contribution to sea-level rise of 0.4 mm per year (Velicogna and Wahr, 2006). The head of the British Antarctic Survey, Chris Rapley, has called the Antarctic in this respect an 'awakened giant'.

Overall, the new observations suggest that the last IPCC report could have underestimated the future sea-level rise. A dynamic disintegration of the ice sheets could possibly occur within a time frame of centuries instead of millennia. Unfortunately the presently available ice models do not permit a reliable prognosis for the further development of the ice sheets. This uncertainty weighs even heavier because, with the positive feedback processes, the deterioration of the ice sheets will be difficult to stop once it has begun. These feedback processes include the lubrication of the undersides of glaciers with meltwater from the surface and the frictional heat due to faster flowing, as well as the lifting of shelf ice from its resting points due to sea-level rise.



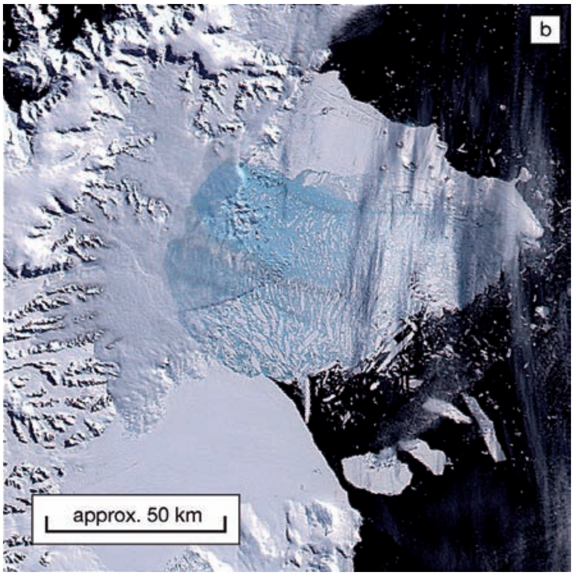


Figure 3.1-3
The Larsen B ice shelf off the Antarctic Peninsula in satellite photographs on 31 January (a) and 5 March 2002 (b).
Source: NSIDC, 2002

3.1.1.3
Further contributions to sea-level rise

Other contributing factors to global sea level are primarily the thermal expansion of water and the melting of smaller mountain glaciers. Regional sea levels are also influenced by changes in ocean currents and by geological processes (local uplift or subsidence of land masses). As long as the global trend is small the regional processes can still predominate. Satellite and water gauge measurements indicate that in spite of global sea-level rise there are still regions with falling sea level, e.g., in the Indian Ocean and around the Maldives (Cazenave and Nerem, 2004). But if global sea-level rise accelerates, it will eventually overcome the local effects and result in an overall rise.

According to water-gauge measurements, sea level on the coasts has risen globally by 20cm since 1870. That rise has accelerated throughout the 20th century, whereas the rate of rise was still near 0 at the beginning of the 19th century (Church and White, 2006). Over the past few millennia, according to geological data, sea level hardly rose at all (Peltier, 2004) – this is also confirmed by analyses of water levels at the time of the Roman Empire (Lambeck et al., 2004). Since 1993 it has been possible to measure sea level globally and precisely from satellites – over this time frame a rate of rise of 3cm per decade has been recorded (Fig. 3.1-4). Up to 5mm of the recent rise could be a fluctuation due to the eruption of the Pinatubo volcano in 1991 (Church et al., 2005). Independent estimates of the individual contributions currently give values of 1.6cm per decade (Willis et al., 2004) due to the warming of seawater, and 0.5cm per decade from mountain glaciers and smaller ice masses outside of Greenland and the Antarctic (Raper and Braithwaite, 2006). This leaves about one centimetre per decade for the two large continental ice masses, which is consistent with the discussion in Section 3.1.1.2. In light of the uncertainties in the individual contributions, however, it is still too early to derive a definitive balance of the present sea-level rise.

The various scenarios of the 2001 IPCC report yielded a rise of 9–88cm from 1990 to the year 2100. The lower of these values lie clearly below the rate of rise already measured. This also suggests that the IPCC has so far underestimated sea-level rise.

3.1.1.4
New estimates of sea-level rise

The physics of the observed dynamic processes in the continental ice discussed above are not adequately understood, and present continental-ice models do not yet consider these processes to a sufficient extent. There is an urgent need here for further research (Section 3.5). Improved estimates are difficult given the present state of knowledge, and are possible only with large uncertainties. Such an estimate, necessarily very rough, is attempted in the following.

Sea-level rise up to the year 2300 is considered, with a stabilization of warming at 3°C above the pre-

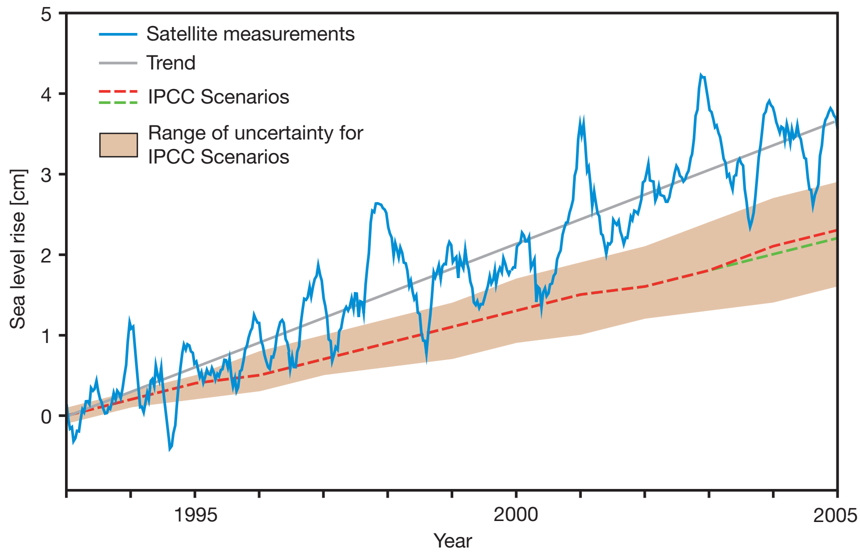


Figure 3.1-4
Global sea-level rise as recorded by satellite measurements (upper line with its linear trend), with the projections of the IPCC (2001a) and its range of uncertainty.
Source: Cazenave and Nerem, 2004

industrial value. The comparatively long time range was chosen because of the intrinsic time scales of the relevant processes, amounting to several centuries both for the melting of ice sheets and for thermal expansion of seawater. After stabilization of the greenhouse gas concentrations and the climate on the surface, the sea level will continue to rise for centuries. To estimate the impacts of anthropogenic emissions during the coming decades, therefore, a consideration only to the year 2100 is not enough.

At a medium climate sensitivity of 3°C, this scenario corresponds to the effect of a doubling of the preindustrial CO_2 concentration, or a CO_2 equivalent of 560ppm. If the worldwide contribution of CO_2 to the radiative forcing due to anthropogenic greenhouse gas emissions remains at 60 per cent, the 560ppm CO_2 equivalent would correspond to a stabilization at 450ppm of CO_2.

- *Thermal expansion:* For this the values of the IPCC are adopted (0.4–0.9m: IPCC, 2001a, their Fig. 11.15a), which are derived from model simulations for a scenario with doubled CO_2.
- *Glaciers:* For the volume of all glaciers outside of Greenland and the Antarctic the same IPCC report gives a sea-level equivalent of 0.5m; with 3°C of global warming one could expect a loss of 80 per cent of the glacial mass for the year 2300. A more recent study (Raper and Braithwaite, 2006), however, uses half of this value; therefore a range of 0.2–0.4m is applied.
- *Greenland:* The model presented by IPCC (2001a) for Greenland with a local warming of 5.5°C (which is a plausible value with 3°C global warming: Chylek and Lohmann, 2005) gives a sea-level rise contribution of 0.9m by the year 2300. The dynamic mechanisms mentioned above, however, are not considered, so this value represents a lower limit; therefore 0.9–1.8m is assumed here.
- *Antarctic:* The behaviour of the West Antarctic ice sheet (WAIS) is critical for the Antarctic. In 2001, IPCC considered the decay of this ice sheet to be very unlikely, because the then existing models suggested that the continental ice did not react to changes in the ice shelves floating in the adjacent sea. This now has to be considered as disproved, as the observations discussed above show. The disappearance of further ice shelves (like Larsen B: Fig. 3.1-3) due to warming of seawater means that the melting of the WAIS must be feared with a similar time frame as Greenland. For this, 1–2m of sea-level rise is assumed by the year 2300. At a constant rate this corresponds to the disappearance of the WAIS in a time frame of 900–1800 years – some glaciologists consider that broad destruction is even possible within 300–400 years.

The net result is a rise of around 3–5m by the year 2300. The value of 3m corresponds to a loss of one-sixth of each, the Greenland and the West Antarctic ice sheets; 5m corresponds to one-third of each (Table 3.1-1).

Table 3.1-1
Estimated global sea-level rise by the year 2300 with global warming limited to 3°C (explanation in text).
Source: WBGU

Mechanism	Rise in m
Thermal expansion	0.4–0.9
Mountain glaciers	0.2–0.4
Greenland	0.9–1.8
West Antarctica	1–2
Total	*2.5–5.1*

The question arises whether these numbers are consistent with today's observed sea-level rise rate of 3cm per decade. Due to inertia and nonlinearity, and the initial slow start-up of the rise, this cannot yet be answered. At today's measured rate of rise, there would be an increase in sea level of only about 1m by 2300. The present rise, however, is a response to only 0.7°C global warming. At 3°C warming a pace four times faster is plausible for the rate of rise and would be consistent with the range estimated above.

This rough calculation, which does not represent a worst-case scenario, underscores the potential risk posed by sea-level rise, which could emerge to be one of the most severe consequences of global warming. More precise and robust estimates are therefore urgently needed. Research needs arise, above all, in the areas of continental ice mass dynamics and the dynamics of the ocean (especially ocean mixing), in order to reduce the uncertainty in the estimation of thermal expansion (Section 3.5).

3.1.2 Stronger tropical cyclones

Ocean-related impacts of climate change threaten humankind and ecosystems not only through the rise in sea level, but also through extreme weather events such as tropical cyclones. The 2005 hurricane season broke a series of records: not since the beginning of record keeping in the year 1851 have there been so many tropical cyclones in the Atlantic (27, six more than the previous record), have so many grown to full strength (15, four more than the previous record), and have there been three hurricanes of the most destructive category – category 5. A more intensive hurricane than Wilma, with a central pressure of only 882mb on 19 October 2005 has never been measured. And with Vince, the first tropical storm to approach Europe was seen; it developed into a hurricane near Madeira on 9 October 2005, and made landfall in Spain after weakening.

The hurricane season of 2004 was already extraordinary. For the first time Florida was hit by four hurricanes in one year, and for the first time Japan experienced ten typhoons, as hurricanes in the Pacific are called. Of even greater interest for climatologists was the fact that in March 2004, for the first time, a hurricane developed in the South Atlantic: Catarina. It formed in a region off the Brazilian coast, where a simulation calculated by the British Hadley Centre had indeed previously predicted that hurricanes would originate due to global warming (Met Office, 2006).

The question arises whether there is a connection between global warming and hurricanes. The central statement regarding this in the last IPCC report was that an increase in the number of tropical cyclones due to global warming is not to be expected, and that observational data also show no significant trend in the number of these storms.

Since this IPCC report was submitted there has been a series of new studies on this topic. They do not exactly contradict the IPCC statement, but they throw a completely new light on the question above, whereby the number of tropical storms is no longer the focus of interest but their strength. The two aspects are determined by different factors. Tropical storms arise from a small disturbance (such as a thunderstorm) over the tropical ocean. In the Atlantic this disturbance often originates on the African continent. What controls the frequency of such 'embryonic' hurricanes is not yet fully understood, but there is no evidence of a direct influence of global warming on this process.

The further development of a tropical storm after it has begun is, however, strongly determined by its surroundings, i.e., by the sea temperatures and the atmospheric circulation. The sea temperatures in particular are affected by anthropogenic warming. Whether the atmospheric circulation changes because of the warming, and to what extent this promotes or hinders the development of hurricanes is still unclear. Here one is dependent on simulations with global models, which, however, still have weaknesses with respect to the resolution of hurricanes. The following points are well-supported by measurement data:

1. Warmer sea temperatures lead to stronger hurricanes with more precipitation.
2. Sea temperatures in the tropics during the relevant season (around June to November) have increased and, in both the Atlantic and Pacific, are at their highest level since the beginning of measurements, which (although with decreasing quality) extend back into the 19th century.
3. The energy of hurricanes has increased both in the Atlantic and Pacific, to their highest values since the beginning of reliable data in the 1950s. While the total number of tropical storms has hardly changed, the number of especially strong hurricanes (category 4 and 5) has clearly increased.

The first point is well supported theoretically: warm temperatures are an energy source for hurricanes, which is why they are a tropical phenomenon. This fact is routinely applied in the predictions of the National Hurricane Center. Emanuel (2005) has verified this connection based on measurement data since 1950. He also defined an index for the strength of a hurricane, the 'Power Dissipation Index' (PDI), which is the cube of the wind speed added over the extent and duration of a hurricane. An increase in the

PDI therefore is seen for stronger, larger or longer-lasting hurricanes. The PDI can be interpreted as an approximate measure for the destructive potential of a hurricane.

Figure 3.1-5 shows the increase of the PDI over recent decades in the Atlantic; there is a similar development in the Pacific. In addition to the increase, the connection to the globally averaged near-surface air temperature is clearly recognizable. The increase of the PDI with temperature, however, is much stronger in the data than would follow from the theory of hurricane energy. This discrepancy is not yet understood. A conceivable hypothesis is that the warm surface layer is thickened, so that the quantity of heat accessible for the hurricane increases out of proportion with the temperature (Scharroo et al., 2005).

Another study (Webster et al., 2005), using satellite data, has shown that the number of category 4 and 5 hurricanes since 1970 has almost doubled globally (that is, in the Pacific, Atlantic and Indian Oceans), although the total number of tropical storms shows no significant trend during this time. This again confirms the statements of the IPCC (2001a), whereby the number does not change, and of Emanuel (2005), whereby the strength increases.

In several studies a working group in Princeton has investigated how global warming affects a hurricane model that is regularly employed for predictions by the National Hurricane Center (Knutson and Tuleya, 2004). The model was run under boundary conditions from several global climate models, both for today's climate and for a warming scenario. In these studies the frequency distribution of the hurricanes shifted clearly toward the stronger storms – the strongest hurricanes, those of category 5, occurred three times more often in the warming scenario than in the reference climate. Because global climate models themselves so far do not have sufficient resolution to describe hurricanes very well, these studies, with a regional, high-resolution prediction model are the strongest tools available to date for simulating the future development of these storms.

Theory, observational data and model calculations therefore indicate that climate warming leads to stronger hurricanes. The effects revealed by measured data are even stronger than theoretically expected. With a warming of the tropical sea-surface temperature of only 0.5°C the hurricane energy has increased globally by 70 per cent in recent decades, and by even more in the Atlantic (Emanuel, 2005). A new data analysis also confirms that the temperature rise is the main reason for this observed energy increase, while other factors play a minor role (Hoyos et al., 2006).

Yet, there are a few hurricane researchers in the USA who attribute the extreme year of 2005 to a natural cycle alone: to a fluctuation of the Atlantic currents ('thermohaline circulation'), which is discussed in Section 2.1.3. This is, so far, also the position of the National Hurricane Center of the USA. These hurricane researchers, however, do not reject the connection between higher temperatures and stronger hurricanes, rather they dispute that the warming itself is anthropogenic, and some of them even dispute anthropogenic climate change in general. Some studies will appear in the near future that analyse the anthropogenic contribution to the increased Atlantic temperatures more accurately.

A natural cycle, in addition to global warming, could have in fact contributed to the extreme year of 2005 in the Atlantic. But such a cycle cannot explain why the temperatures are higher now than ever since

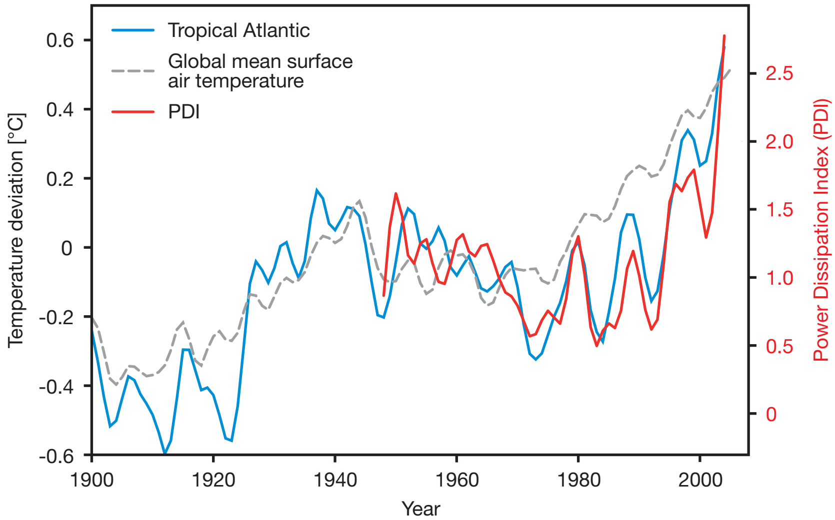


Figure 3.1-5
Temporal development of the energy of tropical storms (Power Dissipation Index – PDI, red) and the average sea-surface temperature in the tropical Atlantic from August to October (blue). For comparison the pattern of the globally averaged near-surface air temperature is shown (dashed grey line). Source: after Emanuel, 2005

the beginning of measurements (and than the last maximum of the cycle in 1950) nor can it explain the rise in the Pacific. There, where the majority of tropical storms occur, their energies have also shown an increasing trend for decades. In addition, the observed temperature development in the tropical Atlantic lies within the range of the global warming trend (Figs. 3.1-5, 2.1-1, and 2.1-2), and is consistent with that derived by modelling calculations as a result of anthropogenic emissions.

To resume, it can be said that among hurricane experts (most of whom are specialists in weather prediction and not climate research) there is a consensus that warmer sea temperatures strengthen tropical storms. Among climate experts there is a consensus that anthropogenic warming has contributed significantly to observed warming in the tropical oceans. A causal connection between global warming and stronger hurricanes is not proven by this and requires further research, but it has to be considered as very likely given the present state of knowledge.

3.2 Impacts on coastal regions

The consequences of climate change, whether in the form of sea-level rise or through greater frequency and force of extreme weather events, will directly affect the future development of coastal regions. The worldwide length of coastlines (excluding small protrusions of less than a few kilometres) is on the order of around one million kilometres. Coastal regions are of extreme importance for humankind. They offer settlement areas, are centres of economic activity (Turner et al., 1996) and, not least, harbour a rich abundance of biological diversity.

The direct effects of climate change, such as the extent and rate of sea-level rise, presently cannot be precisely determined. But it is very probable that the threat to coastal regions will increase considerably, as will the number of people affected by climate change. This is an obvious result of the fact that large numbers of settlements are located near the coasts. Eight of the world's ten largest cities today lie on the coast (UN, 2004), and according to estimates 21 per cent of the world's human population live less than 30km from the sea (Cohen et al., 1997; Gommes et al., 1998). The great attraction of coastal regions is also reflected in the large growth rates of populations there, which is around twice the global average (Bijlsma et al., 1996). The worldwide trend toward urbanization will amplify this development in the future. By the year 2030 approximately 50 per cent of the world population could be living within 100km of the coasts (Small and Nicholls, 2003).

How sea-level rise and weather extremes due to climate change will affect coastal regions and societies depends primarily on the kind and number of affected natural and social systems. The natural systems will mainly be represented by river deltas, low-lying coastal plains, coral islands and atolls, barrier islands and lagoons, beaches, coastal wetlands and estuaries (IPCC, 2001b). The following sections explore in detail which biogeophysical and socio-economic impacts can be expected and to what extent people are threatened.

3.2.1 Biogeophysical impacts

3.2.1.1 Inundation due to sea-level rise

The rise in mean sea level will result in the inundation of coastal areas and island groups in several regions of the world. Inundation here is defined as the permanent covering of land areas with water (as opposed to temporary, episodic flooding). Without counter-measures the result will be the irretrievable loss of this land.

In order to be able to estimate the total extent of the regions endangered by sea-level rise, Brooks et al. (2006) have compiled data on the global land-surface distribution with respect to the elevation above sea level. Figure 3.2-1 illustrates that large regions lie within the range of one metre above high water. Above the one-metre line, the land-surface distribution rises as an almost linear function of the elevation above the mean high water line. At an elevation of only 20m above sea level a total land area of 8 million km² would be affected.

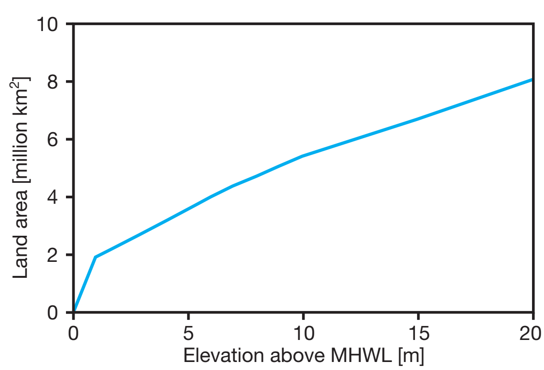


Figure 3.2-1
Distribution of land area, excluding Antarctica, as a function of elevation above present mean high water (MHW). Source: ISciences, 2003

For purposes of illustrating the spatial distribution of these land areas, examples will be shown of regions that lie at elevations within 2m and within 20m above sea level. A rise of 20m (Fig. 3.2-2) represents an extreme scenario that could result from anthropogenic warming over a time frame of around 1000 years, in the event that the ice sheets of Greenland and west Antarctica should melt for the most part (Section 3.1.1). This long time frame has to be considered with sea-level rise because the relevant processes, such as melting of the ice sheets and mixing of the ocean, are slow geophysical processes. Because of the physical inertia in the marine system these processes will first come to a standstill centuries after stabilization of the greenhouse gas concentrations and the surface climate.

The particularly threatened areas in Europe with a rise of 20m would be mainly eastern England, the Po Delta in northern Italy, and the coastal strips running through Belgium, the Netherlands, north-western Germany, and into northern Denmark (Fig. 3.2-2).

A sea-level rise of 2m (Figs. 3.2-3 and 3.2-4) could occur in the coming century. As an illustration of the effects, Figure 3.2-3 depicts regions on the North Sea and the northern European coast. Because this kind of illustration is based on the absolute elevation above sea level, it also includes areas that are protected by dikes today. Some densely populated areas in the Netherlands, England, Germany and Italy today already lie below the normal high-water level (EEA, 2005). For these regions the sea-level rise is especially threatening. Here the question of the rate of change takes on a special importance, because a more rapid rise could hamper the implementation of adaptive strategies (Brooks et al., 2006).

In Asia, with a sea-level rise of 2m (Fig. 3.2-4), for example, the densely populated river delta of the Ganges-Brahmaputra-Meghna with its network of 230 rivers would be affected. The total river region covers an area of 175 million hectares and stretches from India and Bangladesh to Nepal, China and Bhutan (Mirza et al., 2003). Approximately 129 million people presently live in this river delta (Woodroffe et al., 2006), with a large portion of them in rural areas. With Dhaka and Kolkata (formerly Calcutta) there are already two fast-growing megacities here, that is, cities with more than ten million inhabitants.

3.2.1.2
Flooding as a result of storm surges

In most cases the most destructive results of sea-level rise will not be from the very slow rise of the mean water level, but in the increasing occurrences of storm surges.

The origin of storm surges is often related to the interplay of storm systems and tides. When storms push water onto the coasts at high tide it can lead to the flooding of large areas of land. Especially in river estuaries damage can occur over large inland distances (SwissRe, 1998). The word flooding here describes a temporally limited, partial or complete water cover of normally dry areas. This can be caused by the rise of surface water (still or flowing) over its banks, as well as by the results of strong precipitation (Münchener Rück, 1997).

Sea-level rise increases the exposure of coastal inhabitants to storm surges and storm waves, and with it the risk of flooding. The destructive force of these kinds of weather extremes increases as a direct consequence of sea-level rise (Jimenez and Sanchez-Arcilla, 1997). Higher waves will more easily reach the original coastline and also penetrate farther inland. Even the water levels of the two-metre scenario exceed today's standards for coastal defence structures. Although Great Britain, for example, has protective structures that reduce the wave height near the coasts, it is questionable whether these measures can provide long-term protection when the exceptional situation becomes the normal case. If water depths should change or shores become steeper, which would result in a direct energy increase for waves coming onto the land, then the existing structures would no longer be sufficient as coastal protection measures (Burgess and Townend, 2004).

Additional factors could significantly increase the risks from flooding: changes in oceanic and atmospheric circulation patterns caused by climate change can influence storms and their destructive potential at regional and local scale. For example, an increase in the strength of tropical cyclones is anticipated (Section 3.1.2). Furthermore, climate warming could contribute to intensification of the hydrological cycle, which makes increases in the frequency and intensity of extreme precipitation events likely (IPCC, 2001a).

For the consequences of sea-level rise it is less critical how much higher the average water height is than how frequent certain high levels are reached during storm surges. This can be estimated by a comparison of the expected average rise with statistics of past storm surges. Accordingly, the return periods, i.e., the time interval between certain critical gauge levels, could be strongly reduced in the future (Lowe et al., 2001). A model by the Hadley Centre for a region in eastern England, based on a combination of meteorological data and an assumed sea-level rise of 0.5m by 2100, shows a reduction in the return period

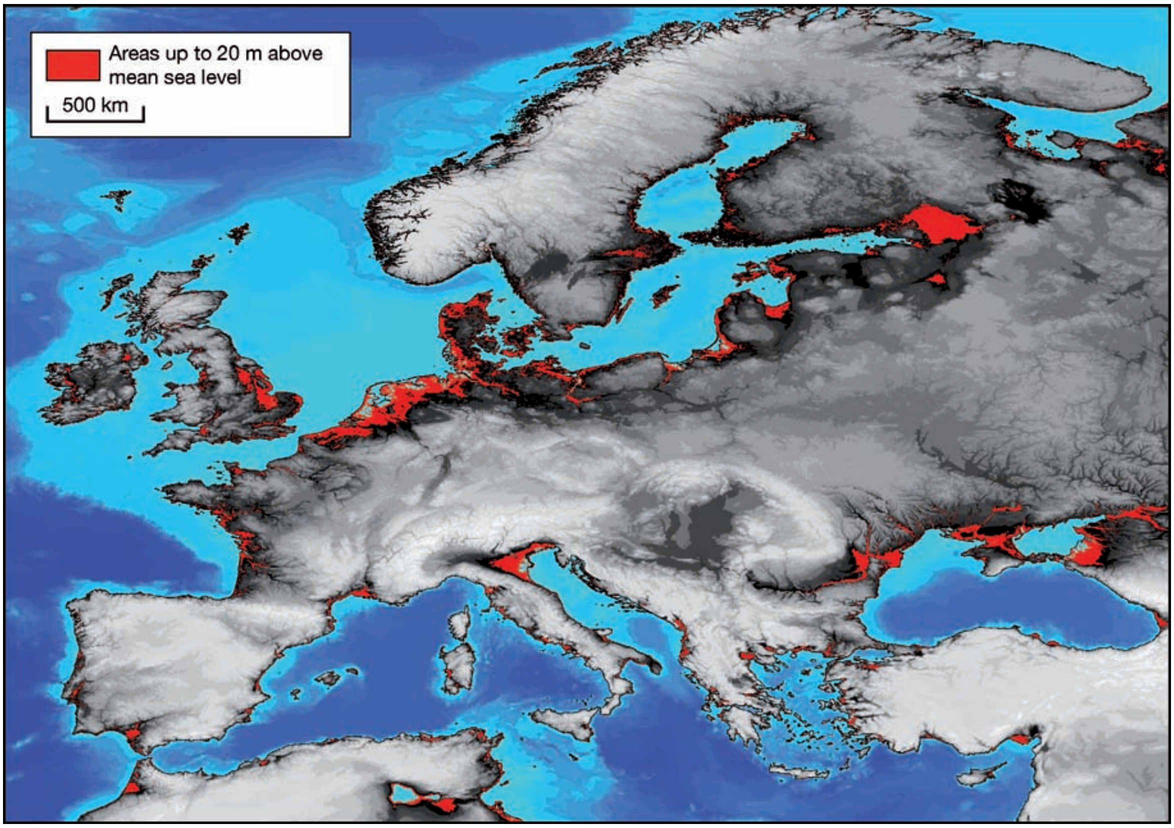


Figure 3.2-2
Coastal areas in Europe, parts of western Asia and North Africa. Areas below 20m elevation above the present mean sea level are coloured red (not taking future coastal defence measures into account).
Source: Brooks et al., 2006

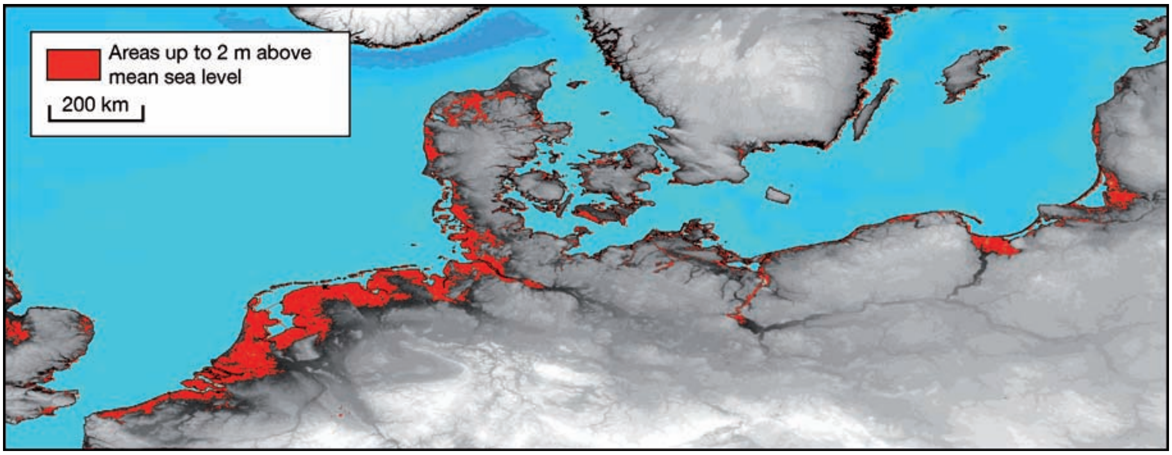


Figure 3.2-3
Coastal areas along the North Sea. Areas below 2m elevation above the present mean sea level are coloured red (not taking future coastal defence measures into account).
Source: Brooks et al., 2006

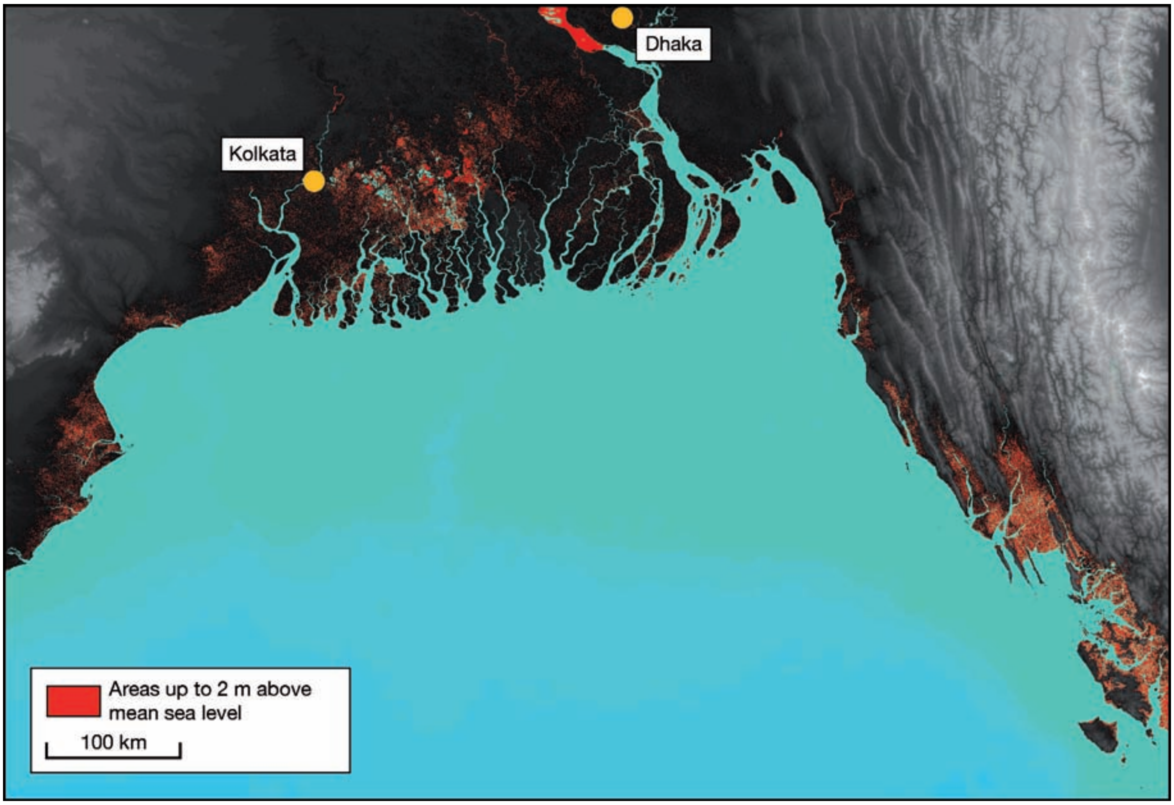


Figure 3.2-4
Coastal areas along the Gulf of Bengal and in the Ganges-Brahmaputra-Meghna River Delta. Areas below 2m elevation above the present mean sea level are coloured red (not taking future coastal defence measures into account).
Source: Brooks et al., 2006

of high-water events from 500 to 12 years (Lowe et al., 2001). Similar trends were calculated for the greater New York City area, based on various climate scenarios. According to these, with a sea-level rise of 24–95cm the return period of a 100-year flood in the 2080s is shortened to 4 to 60 years (Gornitz et al., 2002; Section 3.3). When the return periods of destructive extreme events become too short, the repeated repair of damaged infrastructures would no longer make sense, and they would have to be abandoned.

Land-use changes such as the clearing of forests, urbanization and the conversion of alluvial plains and wetlands can further increase the flooding risk, for example by weakening the water-retention capacity of the soil (Kundzewicz and Schellnhuber, 2004). Straightened or built-up rivers without natural forests and wetlands have less buffer capacity in extreme situations. The flow and sedimentation behaviour of rivers influenced by engineering measures often determines whether storm-caused flooding risks are amplified or attenuated.

3.2.1.3 Coastal erosion

In contrast to floods, which are relatively rare events with sometimes catastrophic results, erosion represents an episodically occurring process (Hall et al., 2002). During the erosion process, waves carry solid materials such as sand, mud and rocks away from the coast and redeposit them for the most part in other formations. A rise of sea level could accelerate these erosion processes (Zhang et al., 2004; Stive, 2004). In particular with a small rise, erosion may prove to be of greater importance than flooding (Smith and Lazo, 2001).

The erosion rates depend on the local conditions. If undercutting occurs along with the resulting collapse of steep coasts or coastal protection structures, erosion can represent a serious danger. In this connection it is important to note that above all the rates of sea-level rise are relevant to changes in coastal morphology. If sedimentation rates can keep up with the sea-level rise, then a new equilibrium can be established and this can have a stabilizing effect on the coastal processes. Sedimentation processes have contributed to coastal development since the beginning of the Holocene, and have been responsible for the preservation of land areas, especially during the inundation of river deltas (Brooks et al., 2006). However, if the sea-level rise accelerates so quickly that a new equilibrium cannot be established, or if sedimentation rates are significantly reduced due to management measures, then a loss of coastal strips will probably result. A well-known example is the Nile, where the sedimentation rates were decreased, primarily by the construction of the Aswan Dam, which led to accelerated erosion of the northern Nile Delta by tides (Stanley and Warne, 1998).

Many authors, including Zhang et al. (2004), refer to the Bruun Rule (Bruun, 1962) in their prognoses of the erosion of coastal regions caused by sea-level rise. This states that the erosion rates are approximately 50–100 times higher than the relative rate of sea-level rise, that is, a sea-level rise of 1m would result in the loss of a 50–100m wide coastal strip. Opinions about the general applicability of the Bruun Rule, however, vary widely, because it is based on the assumption of a simple, two-dimensional system, and the establishment of a sedimentation equilibrium in the bank area. These preconditions, however, can hardly be assumed in real situations. It therefore must be concluded that for estimating the results of erosion along the coastlines, more complex models have to be applied that also incorporate, for example, the sediment transport along the coasts and changes in sedimentation equilibrium, as would be the case with a sea-level rise.

3.2.1.4 Impacts on groundwater

The rise of sea level can also cause the groundwater level of a coastal region to rise. This is determined in part by geographic factors (e.g., elevation above sea level), and in part by geological factors (e.g., properties of rock and soil layers).

Above all, a rise in the groundwater level caused by sea-level rise could impact on river deltas up to 20–50km inland. This estimate is based primarily on the observation that groundwater along the coasts flows above a dense, landward-moving saltwater wedge. This balance between freshwater and saltwater is physically controlled by the relationship of the different water densities. With a rise of sea level, therefore, the overlying groundwater would also rise (Barlow, 2003). This can lead to a saturation of the soil. It produces impacts not only on the freshwater supply of a region, but also on agriculture (salinization risk), the stability of foundations, and the safety and functioning of dewatering and other underground systems such as subways.

In addition, a rise in sea level can promote the invasion of saltwater in coastal aquifers (seawater intrusion). Model simulations by Sherif and Singh (1999) concluded that a rise of 0.5m in the Mediterranean Sea would result in the intrusion of saltwater 9km into the coastal aquifers of the Nile Delta. With the same rise, however, in the Gulf of Bengal, only a zone of 0.4km landward would be affected. These processes would result in an increased salinization of the groundwater and surface waters, with considerable impacts on agriculture and the drinking-water supply. The intrusion of saltwater into the groundwater reservoirs of coastal zones can already be observed worldwide today, e.g. in China and India (Shah et al., 2000). Through the increasing overexploitation of freshwater resources in the densely populated coastal zones, this process can also be considerably amplified.

Although sea-level rise can cause the salinization of river estuaries and near-coastal groundwater reservoirs, this process is determined by a number of other factors. The run-off behaviour of precipitation and its contribution to groundwater recharging also controls seawater intrusion in coastal regions. An increase of freshwater runoff can counteract seawater intrusion. Seawater intrusion would have long-lasting effects. Some of these aquifers would require hundreds to thousands of years to reach a new harmonic equilibrium with the new sea level (Barlow, 2003).

3.2.1.5 Biological impacts

Besides temperature increase and acidification, the expected sea-level rise is an important additional stress factor for the often highly species-rich terrestrial coastal ecosystems or near-coast ecosystems. Two particularly relevant ecosystem types are coral reefs (Section 2.4) and mangrove forests, because they not only harbour great biological diversity, but at the same time play an important role in coastal protection. This latter was illustrated by the tsunami catastrophe in December 2004 in the Indian Ocean: on coasts with intact coral reefs and mangrove forests the flood wave was slowed considerably so that the damage was less disastrous (Fernando and McCulley, 2005; Dahdouh-Guebas et al., 2005; Danielsen et al., 2005).

How coral reefs will respond to sea-level rise can be derived by reconstructions of the past or by model simulations. The adaptive capacity of corals in prehistoric times varied greatly (Montaggioni, 2005).

The average vertical growth rate of coral reefs since the last ice age is reported as at most 10mm per year (IPCC, 2001b). But because the growth rate of corals is influenced by many factors (Section 2.4), and corals in this century will also be impaired by warming, acidification and other environmental factors, a prognosis for the adaptive capacity of these ecosystems cannot be made with respect to the rising water level.

Around 8 per cent of the coastlines worldwide today are bordered by mangroves. More than half of the mangrove forests have already disappeared (WRI, 2001). The observed decline can be attributed in large part to changes in human uses of coastal zones. A study on the changes of mangrove belts in the Amazon region (Cohen and Lara, 2003) shows that sea-level rise can also have a local effect on the distribution of mangroves. The rise of sea level in the future will force the near-coastal mangrove belts farther inland. The mangroves, however, will only be able to survive in areas where enough space is left for them adjacent to the intensive human land use. For the preservation of this valuable ecosystem it is therefore urgently necessary to maintain protected areas or create new ones that include a wide buffer zone on solid land. With the help of the HadCM3 model, Nicholls (2004) evaluated the sensitivity of coastal regions to flooding under the different SRES scenarios (IPCC, 2000). In every case the sea-level rise results in the loss of wetland areas. This study also shows, however, that the direct destruction of wetlands by people could exceed the losses caused by climate change.

Changes in the tidal ranges and high-water levels caused by sea-level rise are an additional burden for coastal ecosystems. The consequences include changes in water depths, light and temperature, and current speeds, and a shift in the freshwater-saltwater distribution. These can lead to physiological burdens for some animal and plant species that could then require a habitat change. Studies show that even minor seawater intrusions into coastal seas lead to large disturbances in the structure and diversity of zooplankton populations. Accordingly, small salinity changes can result in a decline in the biodiversity of coastal ecosystems (Schallenberg et al., 2003). The functioning and preservation of ecosystems are therefore not only threatened by flooding because of sea-level rise, but also by changes in the frequency and strength of seawater intrusions.

The DIVA model (DINAS-COAST Consortium, 2004) is a new interactive tool for integrated analysis of the results of sea-level rise. The model simulates the effects of local sea-level rise (including tectonic rises and falls) on the ecosystems and populations of the coastal regions of the world, and incorporates different adaptive strategies. It is based on the analysis of the worldwide coast lines in more than 10,000 homogenous segments according to morphological and socio-economic aspects, a self-developed extensive worldwide database, and a series of coupled modules. For a scenario with a mean sea-level rise of 50cm by the year 2100 the model reports a loss of more than half of the freshwater wetlands in coastal regions, around 20 per cent of the coastal forests, and a quarter of the mangroves.

3.2.2 Socio-economic impacts

3.2.2.1 Impacts on people

The multiple effects of sea-level rise on the natural environment will have a major impact on people and the systems they depend on. It is likely that some of these effects will interact, intensifying each other, such as floods and erosion-related events. For inhabitants of coastal regions, sea-level rise will be the biggest challenge posed by global climate change (IPCC, 2001b).

The extent of climate-related hazard will also depend on the extent to which the ecosystems of the affected coastal regions have been exposed to prior damage. Pre-existing environmental problems often interact with the impacts of climate change. For instance, flood risk may be increased by changes in land use (deforestation, settlement, etc.) in hydrological catchment areas, or degradation of coastal ecosystems (coral death caused by marine pollution, logging of mangrove forests for building materials and to clear land for aquaculture installations, etc.). Moreover, it has been observed that in some cities the land mass is sinking below sea level. Contributing factors in this case include both the physical pressure of buildings and infrastructure and intensive urban management practices, combined with groundwater extraction, drainage and building activity. Nicholls et al. (1995) estimate that, at their most extreme, local rates of subsidence may be as much as 1m per decade. A rise in sea level then makes the risk of flooding in these regions even greater. The fact that a variety of factors are superimposed on each other – disappearance of natural barriers, sinking of land masses below sea level, and rising sea levels resulting from climate change – increases the risk to populations (Nicholls, 2003).

Based on 1995 population figures, there are currently 60 million people living below 1m elevation and 275 million below 5m elevation above mean sea level. If estimates are adjusted to take into account forecasts of population growth, the figures for the end of the 21st century rise to 130 million (below 1m elevation) and 410 million (below 5m elevation; Nicholls et al., 2005). A more recent study by Brooks et al. (2006) arrived at similar findings (Fig. 3.2-5).

How people in threatened areas will ultimately deal with the challenges of an accelerated sea-level rise is a complex and dynamic process. Migration away from threatened areas will depend on the particular situation in a given locality, and can range from planned migration based on risk assessments and economic considerations to the sudden displacement of people fleeing floods, storms, or sudden erosion-related events. Due to the likely increase in extreme weather events, the incidence of spontaneous migration following natural disasters will probably exceed that of planned migration (Brooks et al., 2006). This is especially likely to happen where a radical change in the landscape occurs and the costs of protecting the affected population become disproportionately high. People in low-lying coastal regions, especially river deltas and small island states, are particularly at risk in this regard (Nicholls, 2003). Studies show, for example, that unless costly protective measures are put in place, a sea-level rise of around 0.5m would put 1.5 million people at risk in the Egyptian governerates of Alexandria and Port Said (El-Raey et al., 1999). In the case of Europe, estimates suggest that 13 million people would be at risk in the event of a sea-level rise of 1m (EEA, 2005).

There is a whole range of model simulations designed to obtain a more precise estimate of the number of people exposed to flood risks. Using the FUND model, Nicholls et al. (2006), for example, have simulated the consequences of disintegration of the West Antarctic ice sheet and the resulting sea-level rise of 5m over a period of 100 to 1000 years beginning in the year 2030. The impact of coastal protection measures was evaluated using cost-benefit analysis. In all scenarios, population displacement reaches a peak between 2030 and 2060. Based on the (extreme) assumption that the ice sheet will disintegrate rapidly within 100 years, up to 350,000 persons per year will be forced to leave their homes over a period of ten years. This would give a total of 15 million people. However, these figures account for a mere 2–3 per cent of the total number of people at risk, because they are based on the assumption that coastal protection measures will be implemented on a large scale. In another study aimed at estimating flood risks, Hall et al. (2005) arrive at the conclusion that, under the A1 and A2-SRES scenarios, the number of people at risk in Britain in the 2080s compared to 2002 would double, rising from 0.9 million to 1.8 million.

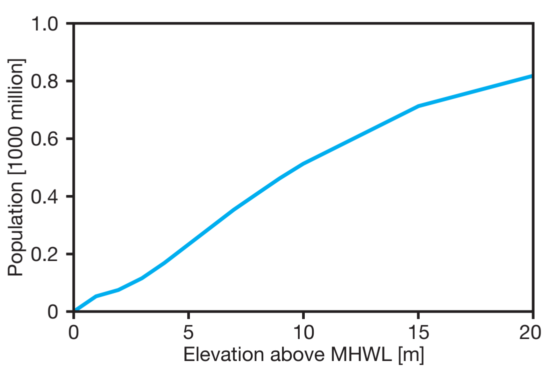


Figure 3.2-5
Population living below a certain elevation above mean high water (MHW) in 1995.
Source: Brooks et al., 2006

'Sea-level refugees'

Whether coastal dwellers who are forced to leave their homeland due to climate-related environmental changes ('sea-level refugees') return home or settle further away from the coast will depend on a whole host of factors. On the one hand, the decision will be influenced by whether coastal protection measures are put in place and how effective or reliable these are. On the other hand, the position adopted by local and regional government will also play a role, for example by discouraging or even prohibiting return to evacuated areas (Brooks et al., 2006). Actual numbers of sea-level refugees will ultimately be determined by the interplay of these factors and measures.

In any case, in the long term sea-level refugees will need to be resettled elsewhere, and this poses new challenges for policy. This is especially true in the case of the inhabitants of some of the low-lying atolls such as the Maldives, the Marshall Islands, Kiribati, Tuvalu or Tokelau. These island states, with a total population of more than 500,000 (CIA, 2005), lie a mere 2m above sea level on average and are therefore at risk of becoming uninhabitable or disappearing completely as a result of climate change. Their inhabitants face a constantly increasing risk of salinization and drinking water shortages and higher risk of storms and floods even if the 1m guard rail (Section 3.3) is successfully adhered to (Barnett and Adger, 2003). These factors are already making their impact felt: the first relocations to higher-lying land took place in December 2005 on the Pacific island of Vanuatu. In this particular case, decreasing intervals between storm surges had made it necessary to relocate the village of Lateu. The United Nations Environment Programme regards this case as probably the first formally recorded resettlement measure of its kind, resulting directly from the consequences of climate change (UNEP, 2005).

Official programmes are already in place to tackle the problem of sea-level refugees. New Zealand has reached agreement with the governments of Tuvalu, Fiji, Kiribati and Tonga on immigration regulations for their inhabitants under the 'Pacific Access Category'. Each year, a certain number of refugees whose status is a direct result of the consequences of climate change are granted a New Zealand residence permit. A whole set of conditions is attached to obtaining a residence permit under these arrangements, however, and older people and poor people are currently excluded (Friends of the Earth, 2005). The right of sea-level refugees to be granted refuge in other countries needs to be enshrined in international law (Section 3.4.2.3).

Threats to human health

In coastal areas, the primary threat to the lives and health of large numbers of people is posed by storms and floods. Even today, a total of 75 million people in coastal regions are exposed to the risk of storm-induced floods. Assuming a moderate climate change scenario with a sea-level rise of 0.4m by the 2080s, this figure would rise to an estimated 200 million (IPCC, 2001b; Patz et al., 2005).

When assessing health-related consequences of storm tides and floods, a distinction can be drawn between immediate, medium-term and long-term impacts. Immediate impacts refers to impacts arising during the event itself and which are due to the effects of flooding. These include death and injury due to drowning or collision with hard objects, and to hypothermia and cardiac arrest (WHO, 2002). In this context, the World Health Organization (WHO) has calculated that in the year 2030 the relative risk of death due to flooding in the coastal areas of the EUR-B Region will be 6.3 times higher than in the base years 1980–1999 (McMichael et al., 2004). Affected countries in the EUR-B Region include some of the former Soviet republics, several Balkan states, Turkey, Poland and the EU accession states Bulgaria and Romania.

The medium-term impacts of floods manifest themselves most notably in an increase in infectious diseases resulting from ingestion of or contact with contaminated water (e.g. cholera, hepatitis A, or leptospirosis), or respiratory infections due to overcrowded accommodation (IPCC, 2001b). The lack of properly functioning sanitary installations and public healthcare provision makes these risks even greater in poorer countries. Following the floods in Bangladesh in 1988, for example, the most common diseases were diarrhoea and respiratory infections, while the most frequent cause of mortality for all age groups under 45 years was acute watery diarrhoea (Siddique et al., 1991).

In the longer term, the consequences of sea-level rise could influence the frequency and distribution of disease vectors. Inundation of coastal regions, for example, affects the incidence of mosquito species that breed in brackish water, e.g. the malaria vectors *Anopheles subpictus* and *A. sundaicus* in Asia. Floods could, however, also destroy the natural habitat of some pathogens, such as the EEE virus (eastern equine encephalitis virus) found in freshwater swamp areas along the US coastline (IPCC, 2001b).

In addition, the rise in sea level and the consequences of storm surges and floods pose a risk to drinking water supplies and food security. This is a matter of increasing salinization of freshwater reservoirs, which not only affects drinking water supply, but can also adversely affect agricultural productivity in the vicinity of the coast. At the same time, floods can also lead to considerable crop losses, as for example in the case of the 1998 floods in Bangladesh, where rice losses accounted for more than half of total agricultural losses and resulted in annual agricultural production falling to a mere 24 per cent of the expected total. Potential consequences include food shortages and undernourishment (del Ninno et al., 2001; WHO, 2002).

As a result of the shock and the consequences of such events, floods can also have long-term effects on the psychological wellbeing of the people affected. Loss of family members and friends, social networks, property and employment can lead to post-traumatic stress syndrome. This manifests itself in feelings of anxiety, depression, psychosocial disorders, and indeed can lead to an increase in suicide rates. It must be taken into account that psychological problems of this sort may not emerge until months or years after an event of this sort (WHO, 2002).

According to a study by the World Health Organization, more than 150,000 people are already dying every year due to the consequences of climate change (WHO, 2002). The primary causes of mortality in this context are increased incidence of diarrhoea, malaria and undernourishment. WHO estimates suggest that additional health risks resulting from climate change will more than double worldwide by the year 2030 (McMichael et al., 2004). These estimates are based on forecasts of a sharp increase in the relative risk of floods, with smaller increases in malaria, undernourishment and diarrhoea. Although smaller relative changes in these phenomena are forecast, they have the potential to bring about disease on a much bigger scale. Infectious diseases thus seem to present a greater risk to humanity than the direct impact of sea-level rise. However, the models used at present do not take account of potential interactions among the various health risks.

3.2.2.2 Economic damage

Assessing the economic impact of climate change on coastal areas also presents scientists with considerable challenges. To be able to make any statement on the overall costs of the impact of sea-level related climate change requires detailed analysis that is also highly disaggregated in geographical terms so as to enable estimation of the expected damage. Such damage may take a wide variety of forms, ranging from damage to property to costs arising due to loss of human life or loss of biological diversity and ecosystem services. Table 3.2-1 gives examples of sectors of society affected by sea-level rise and of the damage and losses to be expected.

In order to assess potential physical damage and impacts on people, it must be borne in mind that a large number of megacities will be affected by a rise in sea level. Of the 20 megacities throughout the world, 15 are exposed to the sea (calculated on the basis of data from Klein et al., 2002; UN, 2004). These include Tokyo, Mumbai and New York. Since development of megacities often entails exacerbation of existing local environmental problems, such as lowering of the groundwater level, these areas often lack any natural buffering capacity to balance the consequences of a rise in sea level. In such cases, drinking water supplies could be jeopardized. This is an example of what is termed 'critical infrastructure' (Bruneau et al., 2003; DRM, 2006), a category that also includes transport, telecommunications and energy supply networks, and emergency, rescue and health services; it further includes the retail sector, public administration, banking and finance. Critical infrastructure refers to institutions that fulfil vital needs and guarantee public safety, uphold law and order and ensure provision of basic public services and a functioning economy (Commission of the European Communities, 2005a). Disruption or damage to this infrastructure can result in supply bottlenecks and significantly impair public safety (BBK, 2006), and may even have a destabilizing effect on a whole region. For example, a gradual rise in sea level and extreme events resulting from it could interfere with the functioning of major ports and at times bring them to a halt altogether, with a knock-on effect on regional trade and transport networks. Geophysical changes to coasts are thus also likely to have large-scale economic impacts on neighbouring and inland regions (Brooks et al., 2006).

In addition to the costs arising from physical damage or disruption to production, there are also costs resulting from the loss of ecosystem services. For example, the negative impact of sea-level rise on coastal ecosystems can adversely affect local fishing yields (Brooks et al., 2006). In many countries, especially poorer countries, the security of people's livelihoods often depends directly on the yield from these ecosystems. Any disturbance in the freshwater balance, for example by seawater intrusion (Section 3.2.1.4), can also affect agriculture. Increasing groundwater salinization has already damaged common agricultural land on the islands of Tuvalu (Friends of the Earth, 2005). As well as jeopardizing food supply, this also brings about a decline in local economic activity.

The overall costs of climate change include on the one hand the damage caused by climate change in monetary units, and on the other the costs of adapting to climate change. Adaptation measures must be implemented in accordance with the principle of economic efficiency so that the benefits of the measures (in the form of damage prevented) outweigh the costs (for example costs associated with construction and maintenance of sea walls). In other cases, it may be more sensible in strict economic terms to forego adaptation measures altogether and accept climate change-induced damage. A cost-effective portfolio of strategies will also depend on environmental and socio-economic conditions in a given region, and these can change over time. For planning strategies and decision-making, it is important that categories of costs and benefits associated are thoroughly explored and taken into account (Section 3.4.1.1).

Categories	Damage or losses
Infrastructure	Buildings, transport infrastructure (roads, rail networks, ports, airports), energy infrastructure, coastal protection structures
Economic sectors	Fisheries, agriculture, forestry (timber in mangrove forests), tourism, transport
Human wellbeing	Mortality, spread of diseases, migration/displacement of people, loss of landscapes and cultural assets
Ecosystems	Services from coastal ecosystems, biological diversity, including some species-rich islands, disruption of the freshwater/saltwater balance

Table 3.2-1
Classification of damage caused by a rise in sea level. Source: adapted from Fankhauser, 1995

A great deal of data is required in order to assess the overall costs of climate change worldwide. Detailed information is particularly needed for identifying and assessing potential damage. Available information, however, is often far from comprehensive and indeed may be quite rudimentary, especially in developing countries. As shown in Table 3.2-1, damage may take a variety of forms and also includes goods that are not traded on the market and therefore have no price. This applies particularly to loss of ecosystem services and biodiversity, which may be quantified in economic terms with the aid of surveys and economic methods of estimation. However, this is an area that is fraught with uncertainty.

People will not simply put up with the effects of climate change. They will protect themselves from damage by putting measures in place to adapt. Economic analysis must therefore include exploring cost-effective combinations of strategies. To do this, models are needed that can simulate not only climate change but also national economic development worldwide. Although some models of this sort are already in use (Fankhauser, 1995; Yohe et al., 1999; Darwin and Tol, 2001), they are based on highly simplified assumptions, with the result that estimates of global costs can only be calculated very roughly and are therefore of limited expressiveness. Data from regional vulnerability analysis, however, enable more accurate estimation of the costs of climate change due to sea-level rise, at least in smaller areas (e.g. Box 3.4-2).

3.3 Guard rail: Sea-level rise

3.3.1 Recommended guard rail

WBGU recommends the following guard rail: absolute sea-level rise should not exceed 1m in the long term (even over several centuries), and the rate of rise should remain below 5cm per decade at all times. For comparison: total anthropogenic sea-level rise up to now has been 20cm; current rates are around 3cm per decade (Section 3.1).

3.3.2 Rationale

The recommended levels are based on WBGU's estimation that a higher or more rapid rise in sea level would in all probability cause damage and losses to humankind and nature that exceed tolerable levels. As is generally the case with guard rails, this estimation contains a normative component and is not solely based on scientific principles (Box 1-1), given that there continues to be considerable uncertainty surrounding the actual consequences of sea-level rise. WBGU hopes that this proposal will stimulate broad debate within society on what is an acceptable degree of sea-level rise and stimulate further research on its consequences.

As in the case of WBGU's climate guard rail on the increase in global temperature (a total of 2ºC and not more than 0.2ºC per decade; Box 1-1), the consequences of sea-level rise depend both on the overall figure and on the rate. Effects on structures that are non-moveable in the long term, such as cities and world cultural heritage sites, depend to a greater extent on the absolute figure, while the rate of rise tends to be more important for dynamic systems such as ecosystems, beaches and some coral atolls, which are able to adapt to some degree. Between the two – in other words between the overall figure and rate – there is a variable degree of trade-off, in the sense that a higher absolute value may be tolerated if the rate is slower, while the maximum rate is tolerable at best for a very short time.

Absolute rise

In order to justify setting an absolute guard rail for sea-level rise that must be adhered to even in the long term, one must consider the consequences of a possible very slow rise in sea level. Based on current knowledge, in the view of WBGU a rise of more than 1m would be intolerable, because severe consequences would be virtually unavoidable even with a very long period of adaptation. This applies, for example, to a whole series of megacities in close proximity to the coast, such as New York, Lagos or Kinshasa.

New York City consists of several islands and peninsulas and has around 1000km of coastline (Bloomfield et al., 1999). Figure 3.3-1 shows the areas of southern Manhattan that would be inundated in the event of a 'one-hundred year flood' (water levels 3m above normal levels) at today's sea levels. In this case, massive damage could be expected to occur, with flooding of important infrastructure including some subway stations. Statistically, if there is a sea-level rise of 1m, this storm surge level would be attained not just once a century, but every four years. A 'one-hundred year flood' would then extend correspondingly further into the streets of Manhattan.

Similar storm problems are to be expected in other cities and in large river deltas (e.g. the Yellow River, the Yangtze, the Ganges-Brahmaputra, the Mississippi or the Nile). In developing countries,

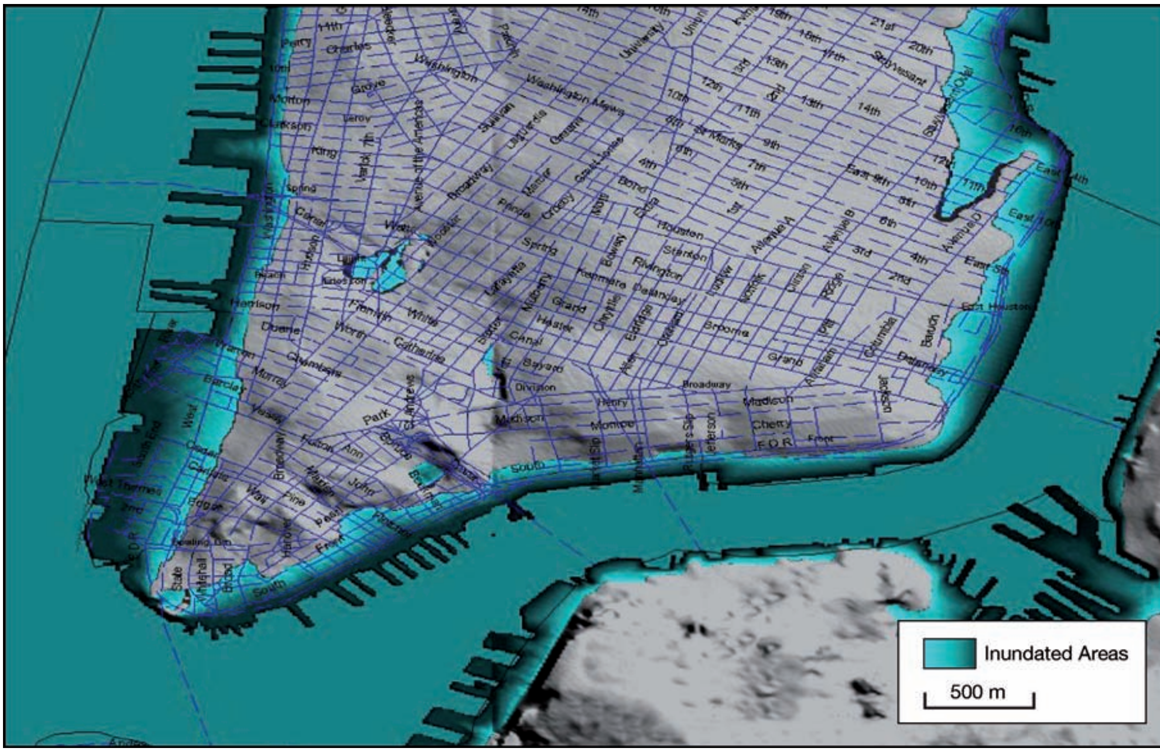


Figure 3.3-1
Inundated areas (blue) in lower Manhattan (New York) in a statistically typical one-hundred year storm event based on the present sea level. A sea-level rise of 1m would result in storm tides of this height approximately every four years.
Source: Rosenzweig and Solecki, 2001; data based on USGS, U.S. Army Corps of Engineers, Marquise McGraw, NASA GISS

poor population groups are often concentrated in these endangered areas.

In its first report, the IPCC listed a whole series of island states that would face a considerable threat from sea-level rise. Many small island states would lose a significant proportion of their land if the sea level rose by 1m (IPCC, 1990). Some of the islands are at risk of becoming uninhabitable due to storm surges resulting from a sea-level rise of this magnitude. Affected islands include, for example, the Maldives, Kiribati, Tuvalu and the Marshall Islands, with a total population of 523,000 people. These problems are exacerbated by the increase in tropical cyclone intensity (Section 3.1.2). Around another 380,000 people living on the Caribbean islands of Anguilla, Cayman Islands, Turks and Caicos Islands and the island state of the Bahamas would also be affected by this. Although some of these islands have high ground of up to 65m above sea level, with the rise in sea level, storm floods would penetrate further and further inland. In many cases, virtually the whole of the island's infrastructure (e.g. airports, roads) is located directly on the coast.

If the sea level rises by more than 1m, there is an additional risk that cultural heritage sites will be irretrievably lost. Cultural goods from the past possess 'outstanding universal value' (UNESCO, 1972). In view of this fact, in 1972 UNESCO adopted the International Convention for the Protection of the World Cultural and Natural Heritage. Some 180 countries are now signatories to this Convention. An important component of world heritage is its universality; it belongs to all individuals and peoples of the world, irrespective of the territory in which it is located.

Great importance should therefore be given to protecting these world heritage sites. A sea-level rise of more than 1m would pose a direct threat for example to the 12th century Shinto shrine of Itsukushima in Japan and the 8th century Shore Temple in Mahabalipuram in India. Both are important religious sites whose special character derives from their coastal location. To protect these sites from sea-level rise, one option might be to consider removing the monuments to another site. This would involve at least some loss, as the monuments are symbolically and historically rooted in their present environment.

A sea-level rise of 1m would also put, among other places, Venice and St. Petersburg at considerable risk. In the storms of 1966, when flood levels peaked at 2m above normal, large areas of Venice were submerged. Homes and businesses were destroyed as a result, but so too were valuable works of art (Nosengo, 2003). In

St. Petersburg too, storms could have devastating consequences. A researcher at the European Bank for Reconstruction and Development (EBRD) suggests that a storm-induced rise in water levels of 2.5m would inundate around 10 per cent of the city, while a rise in excess of this level could affect up to one-third of the city (Walsh, 2003). As a result of these dangers, extensive projects are currently under way to build protective structures; in the case of St. Petersburg, international funding is also involved.

Many valuable coastal ecosystems would also be threatened by a sea-level rise of this sort, for example the Kakadu National Park in Australia and the mangrove forests of the Sundarbans National Park in Bangladesh and India (UNESCO, 2006).

Rate of rise

The rate of sea-level rise should not overstretch the adaptive capacity of human society or marine and coastal ecosystems.

The adaptive capacity of ecosystems can be estimated using the example of coral reefs, mangrove forests and beaches. The last great rise in the sea level occurred at the end of the last Ice Age, over the period from 18,000 to 5,000 years before present. Since then, the rate of rise has always been less than 20cm per hundred years, and usually well below this (Walbroeck et al., 2002; Peltier, 2004). In the Holocene era, after this last great sea-level rise came to an end, coral reefs, beaches, mangrove forests and other ecosystems were able to become established again along the newly formed coastline.

The maximum vertical growth of coral reefs is estimated at 10cm per decade (IPCC, 2001b). If the conditions are highly favourable, they could therefore presumably keep pace with this rate of sea-level rise. Future growth rates will be markedly slower, however, due to ocean acidification and warming and other environmental stresses (Section 2.4).

The adaptive capacity of mangrove forests and beaches is highly dependent on sediment accretion. Sand beach loss already observed along many coastlines is considered to be a consequence of sea-level rise (Leatherman, 2001). Ellison and Stoddart (1991) analyse the development of mangrove forests during the Holocene and arrive at the conclusion that in a situation where there is little sediment accretion, even the current rate of sea-level rise places excessive demands on adaptive capacity and will result in the loss of mangrove forests. Other authors (Snedaker et al., 1994), meanwhile, argue that if the habitat is favourable, retreat of mangrove forests further inland could enable them to accommodate an even higher rate of sea-level rise. In many cases, however, such favourable conditions will not be present. Based on a scenario with an almost linear sea-level rise of 5cm per decade, the global DIVA model (Section 3.2.1.5) projects a continuous loss of mangrove forests whose adaptive capacity has thus already been exceeded. By 2100, according to this projection, a quarter of all mangrove forests would disappear.

According to the scenarios postulated by IPCC (2001a) the rate of sea-level rise towards the end of this century will be 3–7cm per decade, with up to 13cm per decade in the worst-case scenario. In view of these facts, WBGU recommends setting the guard rail for maximum sea-level rise at no more than 5cm per decade. It must be borne in mind, however, that even compliance with this guard rail will not provide protection from damage that is already significant, as is also the case with other WBGU guard rails (Box 1-1).

3.3.3 Feasibility

The current and foreseeable rise in sea level is almost entirely anthropogenic, and hence its future development can also be influenced by humankind. The ability to control it is limited on the one hand by the long time-scale required (centuries) for a response in terms of sea-level change. It is also limited by forecasting difficulties and by the potential for strongly non-linear behaviour on the part of the great continental ice sheets. Nevertheless, the recommended guard rails can be implemented, according to current knowledge, by means of an appropriate climate change mitigation strategy.

Stabilizing the global temperature at 2ºC above pre-industrial levels, according to the mathematical models, would result in a sea-level rise of around 50cm in the long term (after 1000 years) simply due to thermal expansion. Mountain glaciers would add approximately another 20cm to this (Section 3.1.1.4). Prevention of large-scale melting of the continental ice sheets in Greenland and Antarctica would therefore be critical for compliance with the guard rail. Further research must establish the limit that needs to be set as regards the rise in global mean temperature in order to achieve this. It is conceivable that, in the long term, it may be necessary to reduce the temperature to below the 2°C threshold again.

In this century, the guard rail for the rate of sea-level rise would only be breached by the more pessimistic half of the IPCC scenarios (2001a); the more optimistic scenarios comply with the guard rail even without climate protection measures. It should be borne in mind, however, that the currently observed rate of rise of 3cm per decade is already clearly higher than all of these scenarios (Fig. 3.1-4). It must therefore be assumed that, in all likelihood, the IPCC

(2001a) has underestimated sea-level rise, and that climate mitigation measures are indeed required to comply with this guard rail. Based on the assumption that the change in sea-level rise will be relatively smooth and gradual, as depicted in all the scenarios, compliance with the guard rail for the rate of sea-level rise would mean a maximum rise in sea level of around 40cm in the 21st century. This would be double the sea-level rise that has taken place to date as a result of human activity.

The climate and sea-level rise guard rails are closely interlinked, since sea-level rise is directly caused by global warming. In the next few decades, the climate protection strategies required to meet the 2°C goal and to comply with the guard rails relating to sea-level rise will most likely be similar and compatible. Despite the long-term nature of sea-level rise and the uncertainties surrounding the behaviour of the continental ice sheets, these guard rails are not redundant. Even if the global warming guard rail is obeyed and lasting climate warming of 2°C takes place, this would be enough to cause melting of the Greenland ice sheets, thereby breaching the guard rail on sea-level rise. For this reason, it is conceivable that the guard rail on sea-level rise will lead to the imposition of strict limits on emissions, especially in the long term, in other words in the coming centuries, in order to stabilize the continental ice sheets.

This is why it is vital, as regards emissions, to embark on a path that will lead to stabilization of the global temperature at a low level after 2100, and if possible well below 2ºC above the pre-industrial level. The guard rail on sea-level rise therefore determines in particular longer-term climate protection goals from the second half of the century onwards. In the coming decades, it is a key additional justification in support of the 2°C goal. If, on the other hand, the continental ice sheets of Greenland and Antarctica were to shrink suddenly and unexpectedly, the guard rail on sea-level rise could require tougher climate protection measures than the 2°C climate guard rail even sooner. It thus gives particular grounds for closer observation of the ice sheets in order to identify dangerous developments in time.

3.4 Recommendations for action: Develop and implement adaptation strategies

In its previous reports on climate policy, WBGU has made it clear that priority should be given to strategies for preventing greenhouse gas emissions. However, even if there is substantial success in preventing greenhouse gas emissions and complying with the guard rail on sea-level rise, it will no longer be possible to prevent some of the effects of climate change on coastal areas. Appropriate adaptation measures are required in order to cope with these effects. As regards strategies for adapting to sea-level rise and extreme weather events, WBGU focuses on two questions in particular:

1. How can the anticipated destruction of coastal infrastructure and settlements be coped with?
2. How can provision be made under international law to deal with land loss?

3.4.1 Adapting coastal regions to the consequences of climate change

3.4.1.1 Adaptation options: Classification and assessment

The extent to which the consequences of climate change will give rise to damage in coastal areas and turn hazards into disasters varies considerably from one region to another and depends on the vulnerability of the areas affected. This in turn depends on the susceptibility and resilience of natural, social, infrastructural, economic, institutional and cultural subsystems (Titus et al., 1991; Klein et al., 1999). Resilience in this context means the ability of subsystems to cope with repeated disruption so that key structures and processes remain intact (Burton and Lim, 2001; Burton et al., 2002; Adger et al., 2005).

Industrial countries will be better able to deal with hazards than developing countries, because they have more extensive capacities at their disposal, such as an efficient institutional infrastructure, technical know-how and financial resources. Hurricane Andrew, for example, a category 5 event on the Saffir-Simpson hurricane scale, cost the lives of 23 people in the USA in 1992. A typhoon of comparable strength that hit Bangladesh in 1991, meanwhile, led to extensive flooding that resulted in 100,000 deaths and millions of refugees (Adger et al., 2005).

The large number of influencing factors and interactions makes it essential to develop adaptation strategies that are tailored to the given context. Adaptation in this context needs to fulfil two purposes: on the one hand to reduce damage, and on the other to increase resilience of the above subsystems. There are basically three different options for adaptation in response to the hazards outlined above: ‘protection’, ‘managed retreat’ and ‘accommodation’ (IPCC, 2001b).

Protection

Protection involves protecting coasts from rising sea levels by means of structural measures. These might include 'hard' engineering measures such as construction of sea walls, dykes, or flood defence systems, and 'soft' measures such as conservation or introduction of protective coastal ecosystems (e.g. wetlands, mangroves, islands) or beach nourishment as natural barriers. Hard structural adaptation measures are exceedingly cost-intensive in terms of construction and maintenance. In addition, they increase stress on neighbouring ecosystems; for example, they increase the threat of wetland loss. Without intervention, wetlands will tend, as a rule, to migrate inland in the event of floods. This autonomous adaptation is impeded by sea wall construction, because areas on the seaward side of sea walls become inundated, while on the landward side new wetlands are prevented from forming. In the case of US coasts, it is estimated that 50 per cent of all wetlands have disappeared as a result of this process (Titus, 1990). In the coastal regions of the EU, moreover, it has been observed that adaptation involving hard engineering measures can trigger or accelerate erosion processes in neighbouring coastal areas. This in turn can significantly impair the functioning of hard protection measures (Commission of the European Communities, 2005b; Brooks et al., 2006). Due to the multitude of problems associated with hard structural adaptation measures, preference is given nowadays to 'soft' measures wherever possible. Soft strategies interfere less with coastal ecosystems and permit a more flexible response to sea-level rise, the extent of which is fraught with uncertainty. Ultimately, however, the effectiveness of soft and hard measures will depend on the environmental and societal context.

Managed retreat

Managed retreat means that use of areas in proximity to the coast is reduced, or certain areas are relinquished completely. In this context, strategies might include moving buildings and settlements, and introducing government regulation on the use of vulnerable areas. Retreat may be enforced by means of public order legislation, e.g. by regulating land use under national construction and planning law. Another means is to provide incentives in favour of the decision to retreat voluntarily. Measures of this sort encourage households and private businesses to take account of all costs relating to use of the coast in their economic decisions to invest. A targeted information policy implemented by local public bodies could help to enhance awareness of the implications of climate-induced risks.

In certain cases, a sensible option may be to actively support resettlement of people from the coast to less threatened areas, for instance by providing grants via the regional administrative bodies, or within the framework of international development cooperation.

The issue of resettling communities and their residents arises in a very concrete way in the aftermath of a natural disaster, in other words, when infrastructure has been destroyed over a large area. A decision must then be made as to whether reconstruction is economically sensible according to the prognoses relating to future sea-level rise and the incidence and intensity of extreme weather events. The more residents can rely on the government to share the costs of protection measures, the more they will be inclined to remain in threatened regions. If, however, each individual is confronted with the costs of protection, the attractiveness of reconstruction decreases and more people will opt to migrate to less threatened areas. In order to provide the right incentives in such instances, therefore, government (and international) aid for reconstruction must be tied to a corresponding relocation condition. Municipalities, too, must weigh up their adaptation options and decide between protection and retreat. After a natural disaster, they will tend to rebuild destroyed infrastructure rapidly to be able to ensure continuity in public services. This is why it is important to develop strategies for resettlement for threatened areas before a natural disaster strikes (Brooks et al., 2006).

It is conceivable that, despite government incentives to encourage migration away from threatened coastal areas and an adequate information policy on the part of public institutions, some people will not agree to relocate on a voluntary basis. In such a situation, the government must decide whether it will permit the affected people to remain and face damage to property and life at their own risk, or whether it will forcibly relocate sections of the population. The latter option, of course, carries considerable potential for conflict (Box 3.4-1).

Government measures encouraging migration away from coastal areas should go hand in hand with measures limiting migration of people into these areas. For example, levying a tax that reflects the social costs resulting from migration of people into coastal areas ensures that these costs are included in an individual's calculation of the costs associated with migrating into the area, and thus become relevant for his decision.

Government regulation can thus fundamentally support the relocation of people in the desired direction. It is nevertheless possible to provide false incen-

Box 3.4-1

Potential for conflict over resettlement

Depending on regional scenarios of threat, policy-makers must consider the option of planned resettlement of population groups. However, a large number of projects in a great variety of socio-economic and political contexts demonstrate the many problems that can arise as a result of such measures. As examples, dam projects, mining and infrastructure projects (e.g. the Three Gorges Dam in China, lignite open-cast mining in Garzweiler, Germany, road construction in metropolitan Manila, etc.) can be cited.

Although resettlement of endangered coastal residents is generally a necessity in order to protect the affected people, there is also considerable potential for conflict in this situation. For example, decisions to protect important infrastructure installations may amount to unequal treatment of different population groups (populations in the proximity of a protected installation will be protected along with it, while other settlements are evacuated). In addition, exacerbation of conflicts relating to land use in the target area for resettlement may occur (conflicts between long-standing residents and new settlers). Massive resistance is most likely to occur, however, in regions where resettlement programmes were used in the past as a repressive measure by the government.

tives, for example, via interventions in insurance markets. Due to the increasing incidence of floods and cyclones, economic adjustments are in fact to be expected in the insurance markets: insurance premiums for flood damage will rise, and some private insurers will withdraw from the market. As a result, coastal areas lose their attractiveness as areas for settlement. If insurance premiums are kept artificially low by government subsidies, however, as is the case in the USA, prices are distorted and incentives to migrate away from coastal areas are reduced.

Accommodation

The third strategy, termed accommodation, involves modifying land use and subsystems to ensure that they take account of the new threats. Residents of threatened regions continue to use the threatened land, but without trying to protect it from inundation. This can take place, for example, by instituting disaster management systems (constructing emergency refuges, formulating plans of action, undertaking targeted public education and communication work). It is likewise possible to modify land use, for example by cultivating varieties of grain that are resistant to increasing salinization and inundation of the soil or by converting arable land to fish farming facilities. In addition, accommodation also includes engineering measures (such as increasing the height of buildings, making cellars and buildings water-tight).

Portfolio approach

It frequently happens that these options are implemented as a combined set of strategies rather than as alternatives. A 'portfolio approach' is pursued in order to respond adequately to the given conditions in a particular region. One possible combination of strategies involves partial retreat, where protective measures are applied only to areas where there is a high concentration of people, assets and functions. Flooding is allowed to take place in the other areas. Using this approach, implementation of protection measures would be prioritized, focusing on political and economic hubs such as cities, towns and industrial areas. A particular focus of attention in this context is protecting the 'critical infrastructure', in other words, infrastructure so essential that its destruction has a destabilizing impact on a country's public life and economy.

Another strategy that might be considered is to combine protection with accommodation. This could involve, for example, aiming to increase coastal resilience through conservation of mangrove forests as natural barriers. In the context of local land use planning, setback areas could be created or extended to permit ecosystems to shift landward, thereby enhancing an area's capacity for autonomous adaptation (Nicholls, 2003).

3.4.1.2
Choosing adaptation strategies

Cost-benefit analysis may be used (Box 3.4-2) to help choose appropriate adaptation strategies for a specific region. This requires comprehensive information on the state of coastal areas and on the impact of human activities. Assessment of the interaction of land and sea for commerce and industry, for port facilities, buildings, groundwater and extraction of construction material is also called for in this context (Kullenberg, 2001; SEEDS, 2005). The data required for this purpose are gathered and evaluated in the framework of vulnerability studies (Burton and Dore, 2000).

In contrast to prevention strategies, the effects of adaptation projects are essentially local; in other words, they have no direct global environmental benefit. Moreover, because the extent of the environmental effects is fraught with uncertainty, 'no-regret' measures should initially be identified and put in place. These are measures that bring a net benefit for stakeholders irrespective of any actually occuring climate-induced losses. Such measures tend to win greater support among affected stakeholder groups because they take into account the uncertainties of climate change and yield desirable results even if climate change were not to occur. An example might be a coastal region with pre-existing damage and a high population density, for which a rise in sea level would exacerbate existing problems. Improving planning relating to use of coastal areas would be an appropriate strategy here for dealing with sea-level rise. Moreover, it would still bring a positive net benefit even if the anticipated effects of climate change failed to materialize.

In practice, transaction costs, institutional failure or lack of information have frequently led to the shelving of such projects. Adaptation projects can help to dismantle these obstacles (Fankhauser, 1998). Implementation of integrated coastal zone management, for example, could help to improve the exchange of information among the different policy-makers and thereby make it easier to carry out projects.

3.4.1.3
Implementing adaptation strategies

Adaptation requires more than simply implementing engineering options. Not only is the choice of strategies influenced by a multitude of factors; the strategies themselves impact on the subsystems of the region in which they are implemented. It is also necessary to reconcile the various responsibilities and interests of participating or affected groups in society (Nicholls, 2003).

Risk management

Risk management provides an ideal means of implementing adaptation strategies. Risk management plans designate persons responsible (public and private, at municipal, national and international level) for all stages of an event – before, during and after. They describe what measures should be taken (strategic versus tactical measures) at what point in time, and the manner in which the responsible persons should respond and to whom they should report (Boyd et al., 2005). In many instances, policy-makers do not treat the issue of climate change as a priority, and as a result, climate-induced changes in the risk situation are not adequately taken into account. Risks are thus often graded as low and threats are considered as rather unlikely, with the result that the design of available risk management plans is inappropriate. The example of Hurricane Katrina, which caused destruction on an unprecedented scale on the US coast in August 2005, shows that inadequate planning can heighten the socio-economic impact of such events.

Formulating an appropriate risk management plan should ideally be a cyclic process. In advance of an extreme event, a planning phase (Phase 1) – in which preventative and reactive measures are devised – is followed by a preparatory phase (Phase 2). Measures included in this second phase are aimed at reducing the likelihood of potential hazards resulting in disasters. This may be done by establishing action plans, providing emergency training and conducting targeted public information and education campaigns, or by establishing agreements for international cooperation in the area of disaster assistance and for dealing with environmental refugees. If an event actually occurs, the response phase becomes relevant (Phase 3). This phase involves measures to be carried out during and after an event. Such measures include emergency response, measures to prevent consequential damage such as outbreaks of epidemics, or implementing measures aimed at speeding the recovery of affected areas. The reconstruction phase (Phase 4) concludes the process of managing such an event. All activities in this phase are aimed at restoring normal system functioning, via disbursal of insurance payments, setting up temporary emergency shelters or reconstructing the physical infrastructure. In addition to these four phases, problems are identified with regard to the handling of the event and mistakes are analysed. The experience gathered is then evaluated in a new planning phase and implemented in the form of improved strategies (Boyd et al., 2005).

In the case of slow onset hazards, on the other hand, the priority of risk management lies in regularly assessing the potential risks and identifying the most vulnerable individuals and regions. Risk management involves adaptation to constantly changing conditions. A high degree of flexibility in terms of strategies is needed to achieve this. Such strategies include in particular scientific monitoring, public education and communication and legislative provisions (Boyd et al., 2005).

Integrated coastal zone management

In order to take account of the highly complex, interconnected nature of impacts, adaptation measures should be very broad, in other words, they should be enshrined in all key areas of policy. Examples are coastal protection plans and strategies for sustainable development. Another term used in this context is 'integrated coastal zone management'. As part of this system of management, data on both ecosystems and social systems are collected and processed. Integrated coastal zone management as an instrument for managing risk in this context refers to a dynamic process developed and implemented on the basis of a

Box 3.4-2

Coastal management on the German North Sea coast

Global forecasts on the impact of sea-level rise are not directly applicable to regional or local circumstances. Even within Germany's coastal areas, major differences can be observed as regards the hazard situation and socio-economic resilience. To be able to put expedient measures in place to adapt to future consequences of climate change, therefore, small-scale, scenario-based studies need to be conducted that analyse both the natural and social characteristics of a given area. Studies of this sort have already been carried out for two regions of the German North Sea coast: for the island of Sylt and for the north-west German coastal region.

As a result of its particularly risky situation and economic productivity, the North Sea island of Sylt was analysed in the context of a study commissioned by the Federal Ministry for Education and Research (BMBF) entitled 'Climate change: consequences for people and coasts'. The island is an open system with a negative sediment balance in which erosion processes occur that result in a continuous reduction in land mass. Sea-level rise is expected to accelerate these processes. The economic structure of Sylt is heavily biased towards tourism, which is concentrated on the western side of the island.

Various scenarios were devised in order to estimate the consequences of climate change up to the year 2050. The scenario presented here is based on an assumed local sea-level rise of up to 25cm and changes in wind conditions, tidal range and swell (i.e. wave height, direction of approach and period). Extreme weather and its impacts on the natural environment and socio-economic structures were not considered, so further research is needed to explore these aspects. Based on the results of the model simulations, changes in sediment transport are to be expected on the west coast of the island, which would have a negative effect on the wave-attenuating impact of an offshore reef. The three municipalities of Rantum, Hörnum and Wenningstedt are likely to be worst affected by this.

The study recommends adaptation of these coastal areas by adopting a 'portfolio approach', in other words, by a combination of different component strategies. Consideration is given to the three components: protection, managed retreat and accommodation. A combination of 'soft' and 'hard' coastal protection measures was identified as the optimum strategy for protecting Sylt's current coastal form. The measures focus particularly on the environmentally sustainable option of beach nourishment, which is currently already being implemented on the west coast of the island.

To evaluate the recommended adaptation measures in economic terms, cost-benefit analysis was carried out for the west coast of the island. According to this analysis, adaptation costs would consist primarily of the costs of additional beach nourishment measures. At current values, the costs involved in the period up to 2050 are estimated at €33 million. The benefits of coastal protection in terms of prevented losses of assets, infrastructure, beaches and dunes must be balanced against this. The current value of this benefit is estimated at €381 million. The results of the analysis for this period thus show that the benefit-cost ratio of coastal protection for the island of Sylt is clearly positive. The scenario examined illustrates that the island of Sylt can probably be protected effectively against a small rise in sea level of 25cm by beach nourishment measures.

At the same time, it must be noted that Sylt represents a special case, with its particular geographical characteristics and its very high concentration of assets resulting from tourism. The recommended adaptation measures are unlikely to be applicable to the majority of the world's other coastal regions. Beach nourishment, for example, is only possible, and only makes economic and environmental sense, if sand is available within the coastal region in sufficient quantities. In addition, the estimated adaptation costs are based on a coastal protection strategy aimed primarily at protecting the main part of the island, which is higher-lying compared to the shore, from erosion. Beach nourishment would be unlikely to provide adequate protection for flatter sections of coast in the face of rising sea levels – especially in the event of extreme weather situations.

Building on the experiences of the Sylt study, the project 'Climate change and preventive risk and coastal protection management on the German North Sea coast' (KRIM) not only examines the consequences of accelerated sea-level rise for various stretches of coastline, but also the concomitant risks of extreme weather events. Using the same time horizon of 2050, this study analyses future consequences of climate change together with possible social adaptation measures and their impact.

The KRIM project assumes a regional increase in temperature of 2.8°C, a local sea-level rise of 55cm, and changes in mean tidal range, precipitation, swell, and winter wind velocity and direction. In addition, extreme weather conditions with flood levels of +200cm are also taken into account.

In order to analyse the consequences of this climate scenario for Germany's north-western coastal region, the resulting risks of extreme weather events were calculated and the costs and knock-on effects for the regional economy of possible coastal protection strategies were set against these. Alternative strategies were compared using cost-benefit analysis techniques. When assessing potential damage from storm surges, the KRIM project not only considered environmental damage and economic losses from damage to assets and infrastructure, but also the resulting losses to the national economy in terms of value-added activities, income and jobs. A mesoscale modelling technique was used to assess the value of economic losses; in other words aggregated data based on official regional statistics were used. Subsequent to the value assessment, losses were calculated as a function of flood levels.

Among other things, the study examined dyke raising and construction of a second line of dykes as elements of a protection and accommodation strategy for the study area of Wangerland. The location of Wangerland (a region between river Weser and river Jade at the North Sea) is geographically very exposed, with long coastlines requiring protection, but it has relatively few assets. Based on the year 2010 as the assumed investment year (base scenario), the costs of dyke raising were estimated at €10.5 million (for an average increase in height of 0.75m over a 28km stretch of dyke), while the costs of constructing a second line of dykes (variant II) were estimated at €20 million (for a 17km stretch of dyke with a height of 3m above mean sea level). The current value of economic losses in the KRIM climate change scenario, meanwhile, is estimated at €63 million (2000) – calculated using the flood simulations and for the period up to 2050. According to these calculations, the benefit-cost ratio is highest for the dyke-raising option, with the result that action was recommended to implement this coastal protection measure.

The procedure followed in the KRIM project provides a guideline for handling climate change-induced uncertainties with regard to coastal management and shows how the economic future of coastal regions could be forecast and planned. There is still a great need for further research in this area, however: (1) to explore scenarios involving higher rises in sea level; (2) to extend existing insights regarding regional losses and the costs of different preventative strategies (e.g. for the managed retreat option); (3) to include other sections of coastline in this analysis. It will ultimately require a great many small-scale studies of this type in order to be able to make more reliable supra-regional predictions regarding the financial impacts of climate change, and to be better able to work out the possible options for action.

The cases described show that in these instances, where the rise in sea level is clearly below the WBGU guard rail on sea-level rise, the problems can probably be overcome by means of appropriate adaptation measures. Unfortunately, a rise in sea level of more than 1m was not studied for these regions; in many places, successful adaptation in the event of such a high sea-level rise would no longer be possible at an acceptable cost. In developing countries, meanwhile, the problem of financial feasibility would arise even with the scenarios and strategies presented above; the adaptation measures discussed above, therefore, do not represent strategies that are universally applicable.

Sources: Daschkeit and Schottes, 2002; Mai et al., 2004; Elsner et al., 2005

coordinated strategy with the aim of managing environmental, socio-cultural and institutional resources so as to ensure sustainable conservation of coastal areas and ensure that they can be used in a variety of ways in future (Fankhauser, 1998; Yeung, 2001).

Coordinating the sectoral, competing and in some cases overlapping competences of the various decision-making tiers and specialist areas within the administration presents a major challenge as regards devising an integrated coastal management system. Institutional fragmentation often gets in the way of providing adequate responses. WBGU therefore recommends creating integrated institutions that bring together all the key competences. Such institutions would also facilitate reconciliation of the diverse interests of affected groups in society. Municipalities and local administrative departments can play a key coordinating role. Providing for a high degree of local responsibility could help to ensure that available knowledge on coping strategies on the ground is used efficiently, that affected groups in society are appropriately involved in planning and decision-making processes, and, in doing so, that coastal management systems are accepted by the local population (SEEDS, 2005; WCDR, 2005; Box 3.4-2).

There is still a considerable degree of catching up to do in order to integrate information on the potential impact of climate change systematically into implementation of coastal management systems. Despite sound scientific findings regarding the potential consequences of climate change, there has been scant political effort so far to devise adequate strategies for action.

Against this background, the German Federal Government's national strategy for integrated management of German coastal areas is laudable (Bundesregierung, 2006). This strategy takes into account the many different players involved and brings together the competing interests of protection and utilization of Germany's coastal areas under a single, integrated concept. It certainly emphasizes climate change as a major component in the long-term orientation of precautionary planning at regional level. However, in view of the gravity of the anticipated consequences of climate change, it is necessary to improve the scientific basis for developing this strategy further. Measures aimed at adapting to the consequences of sea-level rise and extreme weather events will need to become the primary focus of future strategy.

3.4.1.4
Future challenges

Two issues relating to implementing adaptation strategies need to be emphasized here: the significance of proactive measures and the special challenges of implementing adaptation strategies in developing countries.

Early warning systems

Risk management plans encompass both proactive and reactive components of adaptation. Proactive components are particularly important for cost-effective adaptation design, because they prevent or at least reduce the chance of a risk translating into a disaster. This is true particularly with regard to sudden onset hazards. In the past, priority in financing adaptation strategies was given to reactive measures such as financing reconstruction of damaged infrastructure in the wake of a natural disaster (WCDR, 2005). What appears to be needed, therefore, is a reorientation of funding resources combined with a shift in priorities when choosing appropriate adaptation strategies. At the World Conference on Disaster Reduction (WCDR) in 2005 in the Japanese city of Kobe, it was decided that 10 per cent of funds hitherto used for ex-post measures in the aftermath of natural disasters should be diverted into preventive measures over the next ten years (WCDR, 2005; Münchener Rück, 2005a). The significance of proactive measures is underlined by the plan adopted by the WCDR to promote an International Early Warning Programme (IEWP). The IEWP is aimed at identifying and closing existing gaps as regards early warning (UN ISDR, 2005c). Key elements for improving early warning systems include developing national, integrated risk reduction strategies, capacity-building in the field of risk management and improving technical equipment and training. In addition, strategies are to be developed to improve communication of warnings to affected communities. Early warning therefore comprises a range of aspects, from technical capacity to preparatory measures at municipality level. To date, however, this linking of planning and precautionary measures with adequate response strategies has often been flawed. In future this deficit in existing systems is also to be eliminated. In order to achieve the goals set out in Kobe, international cooperation is required particularly in the area of data exchange, dissemination of warnings and developing institutional structures. At the present time there is a particularly urgent need to raise governments' awareness of the problem and establish priorities for developing appropriate strategies of risk reduction.

Special challenges in developing countries

Climate change will have a major impact on developing countries in particular. These countries account for 97 per cent of fatalities from natural disasters (Freeman et al., 2003). Damage resulting from natural disasters is a considerable impediment to economic development in these countries. Adaptation therefore has particular significance for these regions. Technical know-how, appropriate institutions and especially financial resources are lacking, however, to enable the necessary measures to be put in place. There is broad consensus in the international community that support should be given to help developing countries cope with the impact of climate change. In Article 4, para. 3 of the Framework Convention on Climate Change, the Parties to the Convention commit themselves to provide financial and technical support to affected countries. In the context of the 'Hyogo Framework for Action', the 10-year programme of action adopted at the WCDR, this commitment was reiterated (WCDR, 2005). In addition, in recent years there has been increasing recognition of the fact that strategies for adapting to natural disasters and slow onset hazards need to be made an integral part of sustainable development cooperation (UNFCCC, 1992; UN ISDR, 2005a, b).

3.4.1.5 Financing adaptation measures in developing countries

To provide financial support to enable developing countries to adapt to the general consequences of climate change, a variety of international funding institutions offer financial transfers at multilateral level.

International funds

In recent years, international funding bodies have been set up to promote adaptation measures in developing countries. In the context of the Framework Convention on Climate Change, three funds have been established that provide funding for adaptation to climate change in general, in other words not specifically related to oceans: the Special Climate Change Fund (SCCF), the Least Developed Countries Fund (LDCF) and the Adaptation Fund (GEF, 2005b).

It is the explicit mandate of the SCCF to provide funding for adaptation projects and technology transfer. The fund was set up in 2003 to complement the Global Environment Facility (GEF) with a specific focus on climate change. By late 2004, the volume of funds in the hands of the SCCF in the form of voluntary contributions from OECD countries and other industrialized countries totalled US$34.7 million. SCCF has been in a position to provide effective support for projects since early 2005.

The LDCF gives particular priority to providing support for developing countries to formulate and implement National Adaptation Programmes of Action (NAPA). NAPAs identify areas where action relating to adaptation is most needed. Of the US$32.5 million already contributed to the fund, US$11 million has already been disbursed for the formulation of NAPAs.

The Adaptation Fund, lastly, was set up with the aim of implementing Article 12, para. 8 of the Kyoto Protocol. Its primary source of funds is a share in the proceeds of Clean Development Mechanism (CDM) project activities amounting to 2 per cent of the certified emission reductions issued for a project activity. Disbursal of payments from this fund is unlikely to begin before 2008, that is, before the start of the first commitment period under the Kyoto Protocol. While the revenue effect of this de facto taxation of prevention projects is welcome, its allocation effect must be viewed with considerable criticism.

In addition to the above, GEF also provides funds for projects under its Climate Change Focal Area. In this case, however, the focus is on prevention projects rather than adaptation projects.

Efficient use of development cooperation funds

As well as the above funds, international donors provide financial assistance to developing countries affected by natural disasters in the context of development cooperation. In recent years, for example, the share of funds made available by the World Bank for dealing with the consequences of natural disasters such as tropical cyclones has increased markedly, from 3 per cent to 8 per cent of the World Bank portfolio (Freeman et al., 2003). Financial resources are thus increasingly being earmarked for projects not aimed at fulfilling the original goal of promoting economic and social development.

If the aim of international development cooperation is to support the development of adaptive capacity in developing countries, then assistance must focus to a greater extent on preventative strategies than has hitherto been the case, e.g., on developing early warning systems. A partial shift of this sort from aftercare to hazard prevention takes on added significance against the background of expected intensification of climate-induced extreme events. In order to prevent a loss of efficiency, development cooperation should be brought into line with the policies of the special adaptation funds described above.

At the same time, while ironing out the issue of financing adaptation measures, it is important not to lose sight of the actual goal of development cooperation. Economic and social development in itself remains the best form of adaptation strategy, because it generally increases the adaptive capacity of a developing country and thereby reduces its vulnerability to the impacts of climate change (Schelling, 1992).

Complementary instruments: Prioritizing micro-insurance

The funding required for adaptation measures cannot be quantified in any robust manner due to a lack of even moderately reliable damage estimates (Section 3.2). It can nevertheless be assumed that the above-mentioned financial resources will not be sufficient and that it would consequently be sensible to secure funding for adaptation measures in the broadest possible manner. For this reason, new funding mechanisms should be considered alongside existing funding instruments and reallocation of currently available resources (WBGU, 2002).

Another means is to promote micro-insurance in order to disperse the individual risk of hardship; in countries with low per capita incomes, this takes on added significance. Micro-insurance aims to provide insurance protection at extremely low premiums for households and small businesses with a low, and in some cases irregular, income and to increase available financial resources in the event of losses occurring. Micro-insurance, therefore, is not concerned with the national or international level, but is aimed at protecting individual assets (Münchener Rück, 2005b).

Micro-insurance experience already exists in some areas where individual risks occur independently of each other, e.g. risks relating to illness or accidents (Brown and Churchill, 1999, 2000; Ahmed et al., 2005; Cohen et al., 2005). Case studies carried out in India, Kenya or Uganda show that life insurance and health insurance in particular are already being used successfully (Brown and Churchill, 1999, 2000; Athreye and Roth, 2005). Micro-insurance for risks relating to natural disasters, on the other hand, is still being piloted. Applying micro-insurance to natural disasters is particularly difficult because large numbers of people are usually affected and the individual risk of loss to local policyholders thus depends on the risk for all the others. As a result, demands on the insurer are very high in the event of loss occurring, and may even exceed the insurer's capital stock. If the insurance provider opts for increasing his capital stock or reinsuring as a means of solving the problem, his capital costs increase and this is reflected in the price of the insurance policy. In these circumstances, many households and businesses with low incomes will ultimately forego private insurance altogether.

In order to be able put a reasonably-priced and effective insurance product within their reach despite the difficulties, existing micro-insurance systems for independent risks could be extended to cover losses arising as a result of natural disasters. The costs of insurance cover are kept low by developing effective institutional capacities and 'bundling' policyholders in groups and municipalities. In addition, governments could make it compulsory to take out insurance against natural disasters. This would enable a large number of policyholders to be recruited swiftly and achieve a broad geographical distribution of policyholders, which would greatly reduce the problem of correlated risks of individual losses. The question of whether compulsory insurance of this sort would be a sensible option – especially in countries where social insurance systems are still inadequate – should be investigated in the context of future research.

In order to ensure that providers of insurance for natural disasters operating at national or regional level are successful in the long term, it is important that they are linked to the international capital market. For example, against payment of a premium, reinsurance companies act as 'insurers of the insurers', assuming a proportion of the insurance provider's risk. Risks are thus spread more broadly and insurers are freed from the risk of facing extremely high payouts.

Micro-insurance programmes should be actively promoted by governments (public co-financing): alongside establishing the necessary legal framework, providing financial support might also be considered in the early stages, especially to develop the necessary institutional infrastructure, for example in the context of public-private partnerships and in cooperation with development organizations (Linnerooth-Bayer and Mechler, 2005).

3.4.2 The adoption of provisions governing loss of territory in international law

Adaptation strategies raise a number of legal issues as well. With steadily rising sea levels, it is likely that managed retreat will be the only option in many cases. In particular, national territories may well be lost completely or partially as a result of flooding, with people being forced to abandon settled areas. In terms of international law, this poses various challenges which relate, firstly, to the resettlement of the people displaced by sea-level rise, and secondly, the question of financial compensation in cases when states which are affected by the impacts of climate change-induced sea-level rise have not contributed significantly to its causes.

3.4.2.1 Reduction in the size of national territory

If a state's territory shrinks as a result of sea-level rise, this does not have any specific implications in terms of international law, aside from the issue of compensation (see Section 3.4.2.4). According to the relevant provisions of international law, in such a scenario, the constituent national territory is simply reduced in size. In individual cases, however, it may be necessary to amend specific commitments arising under international law, primarily those relating to the territory which is now submerged. In general, the relevant provisions of international law supply satisfactory solutions to the legal problems which can be anticipated here. It must be borne in mind that a reduction in the size of a state's national territory may result in a shift in the boundaries of its maritime jurisdiction as well, if the points used to position them have changed.

3.4.2.2 Submersion of (island) states

According to current knowledge, the survival of island states lying only a few metres above sea level is in acute jeopardy as a result of climate change-induced sea-level rise (CSD, 2004). These island states include the Maldives, an island group lying no more than 2m above sea level, and the Tuvalu, Kiribati and Tonga island groups, which are located on coral reefs. These small island states, which are also developing countries (Small Island Developing States – SIDS), have formed a community of interest which is making its presence felt as a political alliance in the international negotiations on the United Nations Framework Convention on Climate Change (UNFCCC) (Burns, 1997; Neroni Slade, 2001). Admittedly, the SIDS (along with countries with low-lying coastal areas) have been given special consideration in the UNFCCC; for example, Article 4, para. 8 (a) and (b) calls for consideration to be given to actions, including funding, insurance and the transfer of technology, which may be necessary to meet the specific needs and concerns of these countries. However, this vague reference comprises the full extent of the special consideration of island states contained in the UNFCCC. Indeed, Article 4, para. 8 of the UNFCCC defines the specific needs of other categories of developing countries in such broad terms that almost any developing country Party could claim to be particularly vulnerable in some way. In other words, no specific rights for the island states can be derived from these provisions of the Convention. The island states are not mentioned specifically in the Kyoto Protocol. In the supplementary agreements adopted by the Parties to operationalize the Kyoto Protocol, notably the Marrakech Accords, the needs of the island states are emphasized repeatedly, but this has yet to result in the adoption of any institutional or other specific provisions.

Other regional or global agreements, especially in the law of the sea, also fail to recognize, in any legally meaningful way, the status of island states as countries with special ecological or other problems. The same applies to the United Nations Convention on the Law of the Sea, even though islands play a key role in this Convention as a maritime geographical category of importance in determining maritime zones and related sovereign rights (Jesus, 2003).

From the perspective of international law, the existence of a national territory is a constituent element of the state, which means that submersion of a state's territory could result in its extinction. Nor does international law currently grant any entitlement to the allocation of any kind of 'replacement territory', although this would be possible in political terms. However, experience in the Middle East, not least, has shown that the creation of a state or new national territory may trigger considerable potential for conflict, especially given that hardly any unsettled territories are now available for consideration.

3.4.2.3
Dealing with 'refugees from sea-level rise'

If a state is submerged, its citizens become stateless. 'Refugees from sea-level rise' will probably seek refuge in neighbouring countries, perhaps greatly exceeding these countries' absorption capacities. WBGU therefore considers that formal provisions are required to regulate the legal status of these people.

WBGU recommends that the adoption of relevant provisions under international law be guided by the following principles. Basic provisions should establish the affected population's right to regulated refuge/resettlement. This raises the question of the obligations which would thus arise for potential host countries, whereby a distinction must be made between the practical reception of the refugees and the covering of costs. From a humanitarian perspective, the best option is for refugees to be received by countries in the geographical vicinity of, or with specific links to, the submerged state. The refugees should have a say in choosing their new living environment; forced resettlement should be avoided as far as possible. At the same time, however, an allocation formula should be developed in a process involving the wider international community, in order to ensure that individual host countries' capacities are not overstretched. Fair and efficient burden-sharing requires that the costs of receiving the refugees be allocated according to the 'polluter pays' principle. The allocation formula should thus be guided by the principle of common but differentiated responsibility enshrined in international law. This means that the heaviest burden must be borne by those countries which are making the largest contribution to global greenhouse gas emissions and which also have the greatest financial resources at their disposal (Principle 7 of the Rio Declaration, Article 3, para. 1 and Article 4, para. 1 of the UNFCCC; Kellersmann, 2000; Stone, 2004). It is important to bear in mind that the issue of sea-level refugees is universal, for it arises not only when an individual state is submerged but also when major climate change-induced flooding and devastation occur in states which continue to exist.

The development and application of the relevant legal provisions may prove to be problematical in practice, however. How can refugees who have lost their living environment as a result of climate change, making them dependent on assistance from others, be distinguished from other refugees? And how can the fundamental problem of causality be resolved? After all, hurricanes or extreme weather conditions which trigger refugee flows may not necessarily be caused by climate change but may simply be the result of the natural variability of the climate system (Section 3.1.2; Stone and Allen, 2005). Solutions to these problems must be found when formulating legal provisions governing the treatment of sea-level refugees. Against this background, WBGU recommends a significant increase in research in this area, especially the analysis and exploration of fair and effective burden-sharing systems.

A further difficulty arising in this context is that 'environmental refugees' do not fit into any accepted category in international refugee and migration law (GCIM, 2005). According to the Convention relating to the Status of Refugees (Geneva Refugee Convention), the term 'refugee' only applies to persons persecuted for reasons of race, religion, nationality, [or] membership of a particular social group or political opinion. It does not create any specific obligations under international law for the treatment of 'sea-level refugees'. In WBGU's view, this gap in international refugee law must be closed. One option is to establish bilateral agreements, e.g. with neighbour states, or to adopt a multilateral agreement. This raises the question whether the existing conventions, especially the Refugee Convention, can be amended appropriately without renegotiating the definition of 'refugee' itself, or whether the conclusion of a separate convention would be more appropriate. In line with the non-refoulement principle, persecuted persons may not be deported to a country where they may be subjected to torture or inhumane treatment. By the same token, states should undertake not to return sea-level refugees to their country of origin if climate change has rendered the conditions of life in these countries unsustainable, i.e. if the living conditions are incompatible with human dignity or basic economic survival cannot be guaranteed. The scope of such a new norm must therefore extend beyond the specific problem of sea-level refugees to encompass other forms of environmentally related migration as well.

3.4.2.4
Compensation for loss of land

Compensation issues play a key role in relation to the loss of territory and the submersion of island states. A distinction must be made between various scenarios here.

In cases when only the national level is affected, i.e. the damage is sustained by private individuals through the loss of their property or its value, or loss of income, national law applies; such cases are not relevant to this report. However, possible international conventions may have an impact on private actors if, for example, a state passes the responsibility for collecting the resources to cover international agreed compensation payments through taxes and levies to the private sector.

What is relevant, however, is whether and to what extent the international community or other individual states have an obligation to pay compensation if a country sustains damage directly or indirectly as a result of sea-level rise. According to current international law and practice and prevailing opinion, no such obligation exists: even though the problem of rising sea levels is rarely caused by the affected island or coastal states but is primarily due to greenhouse gas emissions in the industrialized and newly industrializing countries, an obligation to pay reparations or damages does not arise under current international law. The background to this issue is the problem of the cumulative effects of certain types of conduct – a question which has yet to be satisfactorily resolved in international law – and the causal links, which are sometimes difficult to establish. As international law stands, the ban on causing major transboundary environmental injury, recognized in customary international law, thus does not apply (Epiney, 1995; Beyerlin, 2000; Wolfrum, 2000; Sands, 2003). Nonetheless, cause and effect have been established in many instances, and there is no doubt that climate changed-induced sea-level rise is presenting some developing countries with problems which they lack the financial resources to cope with unaided.

Against this background, WBGU recommends the conclusion of an international convention which would oblige the industrialized countries in particular to guarantee adequate funding for an internationally administered compensation fund. Funding would be disbursed from this fund to countries particularly affected by rising sea levels. A country's contribution commitments should be weighted according to the greenhouse gas emissions it produces, so that payments can be regarded as compensation for a country's actual contribution to climate-related damage (Section 3.4.1.5). Once this compensation fund has been established as a means of providing assistance to the affected states, it could also take on a role in burden-sharing within the international community, e.g. managing the reception of refugees fleeing from sea-level rise and the payments made to host countries (Section 3.4.2.3).

Utilizing the mechanisms for the transfer of financial resources and technology established for the climate regime might also appear, at first sight, to be a viable option. For example, the Mauritius Strategy for the Further Implementation of the Programme of Action for the Sustainable Development of Small Island Developing States (para. 78(a)) posits, in the context of climate change adaptation and sea-level rise, that strategies can be developed with support from the Least Developed Countries Fund and the Special Climate Change Fund set up within the framework of the United Nations Framework Convention on Climate Change. The key objection here is that such support cannot be regarded as genuine compensation for climate-induced damage. A further possibility is for the United Nations Compensation Commission to take action in this area; for example, it recently adjudicated compensation for environmental damage caused in the 1990–1991 Gulf War (Sands, 2003). However, this particular instrument is not precise enough to pay targeted compensation for the damage caused by climate changed-induced sea-level rise. An existing body could at best be entrusted with the task of administering the separate compensation scheme outlined above.

3.5 Research recommendations

Hurricane formation and strength

The links between hurricane activity and global warming need to be researched more thoroughly, both through further analysis of data gathered from past developments and by modelling the future development of the hurricane climate, including potential threats to areas not affected previously (South America, southern Europe).

Extent and rate of sea-level rise

The greatest uncertainty surrounding future sea-level rise concerns the behaviour of continental ice sheets in Greenland and Antarctica. To reduce this uncertainty, there is a need to gain an improved understanding of ice dynamics; major progress is needed in continental ice modelling. These activities include researching the stability of the ice shelves as well as their interplay with continental ice. Further uncertainties surround ocean dynamics, especially the intensity of ocean mixing. Such dynamics greatly influence sea levels. There is a need to improve their characterization within global climate models.

Global potential for damage caused by sea-level rise

The issue of 'dangerous sea-level rise' forms a sub-set of the wider question of 'dangerous climate change' and must be answered quantitatively if possible. To do so, there is a need to aggregate globally the health, socio-economic and ecological consequences associated with various scenarios (x metres rise in y years). Present assessments are not robust in this respect. They must be replaced by a new generation of impact analyses. This could produce a more precise definition of the provisional absolute guard rail proposed by WBGU (maximum of 1m sea-level rise).

Vulnerability of coastal megacities in developing countries

Climate change and urbanization are dominant trends of global change. The interplay of the two trends in the major coastal cities of the developing world could cause an almost unmanageable situation, particularly if the arsenal of responses is limited by social, economic and institutional deficits. There is an urgent need to conduct interdisciplinary studies in order to assess the severity of the problems for particularly critical megacities such as Lagos, Mumbai or Havana.

Regional portfolio strategies for coastal management

The dramatic geophysical impacts of climate change upon coastal zones (which will arise even if vigorous measures are taken to reduce global greenhouse gas emissions) mean that the traditional approaches to coastal management need to be revisited. There is a particular need to determine the priority given to the various strategic elements of protection, managed retreat and accommodation. To be able to conduct such an assessment, types of cost-benefit analysis must be developed that take account of the novel potential for damage. At present such analyses have only been carried out for limited sections of coasts, e.g. in Great Britain. There is an urgent need to conduct an integrated re-appraisal of robust and effective portfolio strategies for German coasts.

'Sea-level refugeese': Legal and institutional aspects

The threats presented to coastal regions and the potential destruction of entire state territories by climate-induced sea-level rise generate a novel migration problem whose legal dimensions have yet to be explored. There is a particular need for research on how to shape provisions under international law with respect to the reception of 'sea-level refugees', the payment of compensation, and burden-sharing in line with the 'polluter pays' principle. To resolve the legal problems, it is also very important to make progress in the scientific attribution of damage or territorial loss arising as a consequence of human-induced climate change. There is also a need to conduct operative appraisals, for instance to evaluate the capacity of the existing United Nations institutions to cope with refugee flows, especially given that needs will presumably grow exponentially in the future.

4.1 Chemical changes in seawater

4.1.1 CO_2 input

The oceans hold around 38,000 gigatonnes of carbon (Gt C). They presently store about 50 times more CO_2 than the atmosphere and 20 times more than the terrestrial biosphere and soils (Fig. 4.1-1). However, the ocean is not only an important CO_2 reservoir, but also the most important long-term CO_2 sink. Driven by the difference in the partial pressure of CO_2 between the atmosphere and seawater, a portion of the anthropogenic CO_2 dissolves in the surface layer of the sea and, over periods ranging from decades to centuries, is finally transported into the deep sea by ocean currents.

There has already been a demonstrable increase in CO_2 concentrations in the upper layer of the sea over recent decades (Sabine et al., 2004) that can be attributed to the proportional rise of CO_2 in the atmosphere. The ocean is presently taking up 2Gt of carbon annually, which is equivalent to about 30 per cent of the anthropogenic CO_2 emissions (IPCC, 2001a). Altogether, between 1800 and 1995, the oceans have absorbed around 118Gt C ± 19Gt C. That figure corresponds to about 48 per cent of the cumulative CO_2 emissions from fossil fuels (including cement production), or 27–34 per cent of the total anthropogenic CO_2 emissions (including those from land-use changes; Sabine et al., 2004). The anthropogenic CO_2 signal in the sea can be traced, on the average, to a water depth of approximately 1000m. Due to the slow mixing of ocean layers it has not yet reached the deep sea in most parts of the ocean. In the North Atlantic, however, due to the formation of deep water there, the anthropogenic CO_2 signal already extends down to 3000m.

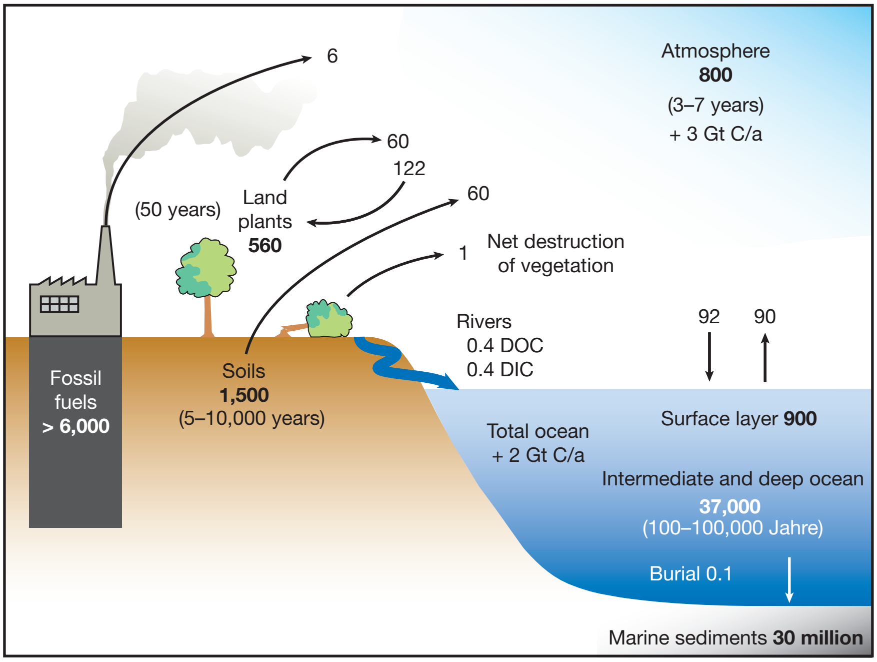


Figure 4.1-1
Overview of the global carbon cycle. Values for the carbon reservoirs are given in Gt C (numbers in boldprint). Values for the average carbon fluxes are given in Gt C per year (numbers in normal-print). Mean residence times are in parentheses. Flux into soils amounts to around 1.5Gt C per year. DOC = dissolved organic carbon, DIC = dissolved inorganic carbon.
Sources: adapted after Schlesinger, 1997 and WBGU, 2003.
Numbers expanded and updated for ocean and fossil fuels: Sabine et al., 2003; marine sediments: Raven et al., 2005; atmosphere: NOAA-ESRL, 2006

In the atmosphere CO_2 behaves chemically neutral, that is, it does not react with other gases, but it contributes to climate change through its strong interaction with infrared radiation. But in the ocean CO_2 is chemically active. Dissolved CO_2 contributes to the reduction of the pH value, or an acidification of seawater. This effect can already be measured: since the onset of industrialization the pH value of the ocean surface water has dropped by an average of about 0.11 units. This is equivalent to an increase in the concentration of hydrogen ions (H^+ ions) by around 30 per cent. Starting from a slightly alkaline pre-industrial pH value of 8.18 (Raven et al., 2005), the acidity of the ocean has thus increased at the surface. The various IPCC emission scenarios indicate that if the atmospheric CO_2 concentration reaches 650ppm by the year 2100, a decrease in the average pH value by 0.30 units can be expected compared to pre-industrial values. With an atmospheric concentration of 970ppm, the pH value would drop by 0.46 units. But if the CO_2 in the atmosphere can be limited to 450ppm, then the pH reduction will only amount to 0.17 units (Caldeira and Wickett, 2005).

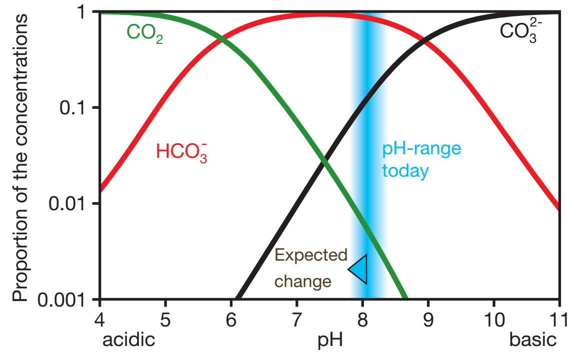


Figure 4.1-2
Carbonate system of seawater. Relative proportions of the three inorganic components CO_2, HCO_3^- und CO_3^{2-}. The blue shaded area shows schematically the pH range that occurs in today's ocean. The arrow shows the expected shift of the average pH value when the atmospheric CO_2 concentration reaches about 750ppm.
Source: Raven et al., 2005

4.1.2
Change in the carbonate budget

The carbon stored in the seas occurs in different chemical forms. A small part is stored in the biosphere and in organic compounds, but the greatest part by far is contained in inorganic compounds, which are referred to as DIC (dissolved inorganic carbon). Of these compounds, however, only 1 per cent is directly dissolved CO_2, 91 per cent occurs as bicarbonate (HCO_3^-), and 8 per cent as carbonate (CO_3^{2-}). The relationship of these three compounds can be represented by the equilibrium equation:

$$CO_2 + H_2O + CO_3^{2-} \leftrightarrow 2\ HCO_3^-$$

The relative proportions of these carbon compounds reflect the pH value of the water (Fig. 4.1-2). Only CO_2 can be exchanged with the atmosphere. Through the uptake of CO_2 the partial pressure of CO_2 increases in the seawater, and at the same time the equilibrium shifts in favour of bicarbonate and to the detriment of carbonate.

Due to the uptake of anthropogenic CO_2, the carbonate concentration in the ocean surface layer has already dropped by 10 per cent compared to the pre-industrial level (Orr et al., 2005).

The saturation of seawater with carbonate ions is especially important for marine organisms that build their shells or skeletons with lime (calcium carbonate, $CaCO_3$: Section 4.3.2). Calcium carbonate occurs in marine organisms primarily in the forms of aragonite and calcite, which differ in their crystal structures (Table 4.3-1). Seawater is supersaturated with respect to the more easily dissolved aragonite when the carbonate concentration lies above 66µmol per kilogram. If it falls below this value the aragonite formed by the organisms dissolves in the water – this is referred to as aragonite undersaturation. Because of the increasing solubility of calcium carbonate with decreasing temperature and increasing pressure, the deeper layers of the sea are, as a rule, undersaturated, that is, sinking $CaCO_3$ dissolves in the water at greater depths. The boundary between the undersaturated and super-saturated layers is referred to as the saturation horizon.

The present carbonate concentration in the sea surface layer varies among regions: the highest concentrations (averaging 240µmol per kilogram) occur in the tropics, while values in the Southern Ocean average only 105µmol per kilogram (Orr et al., 2005). With progressive CO_2 input into the sea, therefore, the marine organisms in the Southern Ocean are the first to be threatened by aragonite undersaturation (Section 4.3.2). Orr et al. (2005) calculate the possible future development of the carbonate concentration of the Southern Ocean for various emission scenarios. According to these calculations, under a 'business-as-usual' scenario it could already be undersaturated with respect to aragonite by the middle of this century (Fig. 4.1-3). With an atmospheric CO_2 concentration of approximately 600ppm or more, the greater part of the surface layer of the Southern Ocean would be undersaturated. But even before this threshold is reached the saturation horizon drifts upward, that is, the upper layer of the sea that is

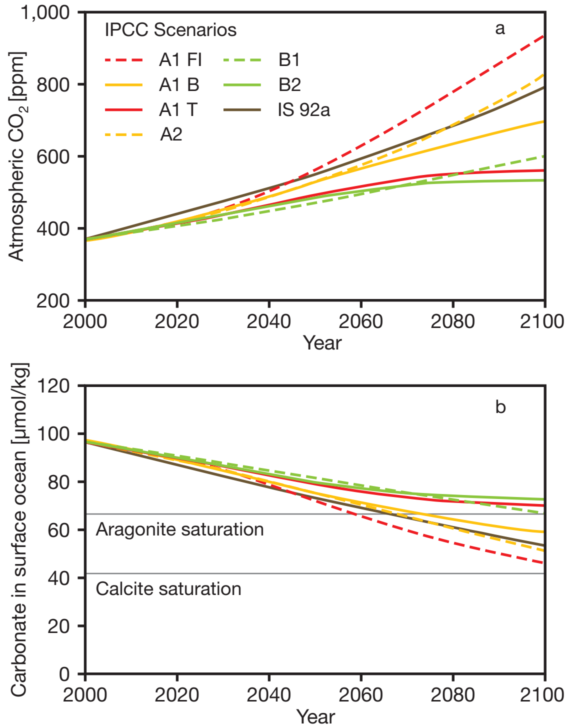


Figure 4.1-3
Projections of different CO_2 concentrations (a) and their effects on the carbonate budget of the Southern Ocean (b). The variation according to various IPCC scenarios is shown. Source: Orr et al., 2005

supersaturated with respect to aragonite becomes thinner, and $CaCO_3$ formation becomes more difficult. Individual parts of the surface layer would be affected even earlier. With respect to the less-soluble calcite the surface layer remains saturated despite higher CO_2 concentrations, but the calcite saturation horizon also shifts upward. With the displacement of the saturation horizon the conditions for biogenic $CaCO_3$ formation change, which can have considerable consequences for marine organisms and ecosystems (Section 4.3).

4.1.3
Special role of CO_2

The acidification of the sea is an effect that can be exclusively attributed to the CO_2 increase in the atmosphere. In this it is different from climate change, which is caused by the radiative effect of atmospheric CO_2 increase, but also of the increase of methane, nitrous oxide and several other radiatively active gases. With respect to climate change, calculations are often made in terms of CO_2 equivalents, that is, the radiative forcing attributable to the various gases is recalculated to the corresponding forcing of CO_2. The argument is that for climate protection it does not make any difference whether the radiative effect is caused by CO_2 or by any other emitted greenhouse gas. But this is not true for the effect of ocean acidification. To protect the oceans, reducing CO_2 emissions is relevant for two reasons: to limit both global warming and ocean acidification.

Acidification is, above all, a consequence of the rapid increase of the quantities of CO_2 in the ocean. With a slow input of CO_2, as has repeatedly occurred in the Earth's history (such as the end of the last ice age when the CO_2 concentration rose by 80ppm over a period of 6,000 years), or in climate epochs with elevated CO_2 concentrations (around 100–200 million years ago) the CO_2 mixes down into the deep sea, where a slow dissolution of carbonate sediments counteracts the acidification. In such constellations the pH value of the sea remains almost constant (Raven et al., 2005).

4.2
Future development of the oceans as a carbon sink

As discussed in Section 4.1, the oceans are the most important net sink for CO_2. Without oceanic uptake of anthropogenic CO_2, the relative CO_2 concentration in the atmosphere would lie more than 55ppm above the present level (Sabine et al., 2004). The future development of the oceans as a CO_2 sink will therefore determine in large part how strongly anthropogenic CO_2 emissions are reflected as an increase in the atmospheric concentration of carbon dioxide. Over the long term, that is, a period of several centuries (in which mixing takes place throughout the world's oceans), the ocean can take up about 65–80 per cent of the anthropogenic CO_2, depending on the total quantity of carbon emitted. At even longer time scales this proportion increases to 85–92 per cent due to the dissolution of carbonate sediments (Caldeira, 2005). In the coming decades and centuries, however, only a portion of this great sink potential can be effective: the limiting factor is the transport of carbon taken up at the surface into the deeper ocean layers. In fact, the oceans have so far only absorbed 30 per cent of the amount of anthropogenic carbon that they could take up over a long time period at present atmospheric concentrations (Sabine et al., 2004).

The great importance of the ocean as a sink is not applicable to the other greenhouse gases regulated by the Kyoto Protocol: the strongest sink for methane as well as for HFCs, for example, is the chemical reaction with the hydroxyl radical OH in the lower atmosphere, while N_2O is destroyed primarily in the stratosphere by UV radiation from the sun. The industrial gases PFCs and SF_6 do not decay until they are above the stratosphere. It is worth noting, however, that the sea is an important source of N_2O, whose future development in response to climate change is unclear.

Before industrialization the ocean was at a state of near equilibrium, and not a CO_2 sink. At its surface it gave off around 0.6Gt C annually to the atmosphere, while at the same time approximately the same amount of carbon entered the ocean from the terrestrial biosphere (and therefore ultimately from the atmosphere) in the form of organic matter flowing in from rivers (Watson and Orr, 2003). The proportion of atmospheric CO_2 did not change under these conditions, remaining constant over millennia at around 280ppm. The reason for the present function of the ocean as a sink is the anthropogenic perturbation of the carbon cycle: when the CO_2 concentration of the atmosphere increases, the ocean takes up CO_2 until the partial pressures of the surface water and the atmosphere are in equilibrium. Since the beginning of industrialization the atmospheric CO_2 concentration has risen almost exponentially. This has caused an annual increase in the CO_2 uptake by the oceans since that time, in quantities almost proportional to the atmospheric CO_2 concentrations, as model studies indicate (Gloor et al., 2003). For various reasons, however, this cannot be carried over into the future, which will be discussed below.

When one compares the quantities of CO_2 taken up by the ocean with anthropogenic emissions, the efficiency of the ocean sink appears to be falling already: Sabine et al. (2004), based on an analysis of observational data, show that from 1800 to 1994 the ocean absorbed 28–34 per cent of the anthropogenic emissions, while from 1980 to 1999 this value was only 26 per cent. Due to the large uncertainty in the determination of the global carbon balance, this decrease is not statistically significant, but on the basis of known geochemical processes it is also not unexpected. The more CO_2 that has been taken up by the ocean, the lower the carbonate concentration in the surface layer becomes (Section 4.1.2). This decreases its capacity to take up additional CO_2. Modelling studies show that the relative CO_2 uptake by the ocean (that is, the proportion of anthropogenic emissions absorbed by the ocean in the course of a few decades) is reduced by this effect by several per cent when an atmospheric CO_2 concentration of 450ppm is reached. At 750ppm of CO_2 in the atmosphere the relative CO_2 uptake falls by as much as 10 per cent (Le Quéré, personal communication). This geochemical effect is fully considered in models of the carbon cycle and is therefore rarely expressly discussed (Gruber et al., 2004). This effect is also active in the extreme long term, that is, time periods in which the ocean completely mixes, so that the proportion of anthropogenic CO_2 emissions remaining in the atmosphere continues to increase as more CO_2 has been emitted.

Climate change resulting from greenhouse gas emissions further affects the capacity of the ocean sink: the solubility of CO_2 in seawater decreases with rising temperature. Through this effect, by the end of this century the cumulative CO_2 uptake could fall by 9–14 per cent of what it would be without a temperature change (Greenblatt and Sarmiento, 2004). This effect is well-understood; the uncertainty predominantly results from the uncertainty of the degree of expected temperature change.

A further effect of climate change is an increasing ocean stratification, that is, the vertical mixing will be reduced. This has a number of complex effects. For one, the transport of carbon-enriched surface water to greater depths as well as the transport of carbon-depleted water to the surface will be weakened, resulting in an overall decrease of the sink effect of the ocean. For another, there could be changes in biological productivity through altered nutrient availability. Biological productivity is of great importance for the carbon balance of the ocean surface layer: CO_2 is taken up by marine organisms through photosynthesis and incorporated into organic substance; dead organisms sink and then decay in different water depths. Part of the released nutrients and carbon return to the surface through vertical mixing, but the net export to the deep sea is considerable. Ten gigatonnes of carbon are transferred annually by this 'biological pump' from the ocean surface layer to the deep sea. The combined effect of increased stratification and altered biological productivity on the sink effect of the ocean is highly uncertain. Greenblatt and Sarmiento (2004) give a range of -2 per cent (decreased sink function) to +10 percent (increased sink function) for the change in cumulative CO_2 uptake through this effect by the end of the century.

Many of the effects discussed are still difficult to quantify, but it is likely that climate change will contribute to a considerable overall weakening of the efficiency of the sea as a carbon sink. According to an overview based on various modelling studies by Greenblatt and Sarmiento (2004), the cumulative CO_2 uptake by the ocean could be 4–15 per cent lower by the end of the century due to the climate-related influences discussed above (temperature rise, increased stratification, and biological effects) than it would be without these. This attenuation of the CO_2 uptake has to be added to the geochemical effects that already lead to a weakening of the relative sink with a similar order of magnitude.

As already indicated, biological processes represent the greatest uncertainty in estimating the future development of the ocean sink. These biological processes include the impacts of anthropogenic interference with the atmosphere and ocean acidification on marine primary production, the biological pump and calcification (Section 4.3.5). A weakening of the ocean sink due to changes in the wind-driven rise of water at the equator ('equatorial upwelling') is a further aspect under debate (Winguth et al., 2005). In addition, non-linear events that are difficult to predict such as a strong decrease in oceanic convection or in the thermohaline circulation, or biological regime shifts (Section 2.2.1) could have a considerable influence.

In summary it can be stated that, with increasing atmospheric CO_2 concentrations, the proportion of anthropogenic CO_2 emissions taken up by the ocean will decrease, even if the absolute rate of uptake increases (IPCC, 2001a).

4.3
Effects of acidification on marine ecosystems

CO_2 input into the sea leads to shifts in the carbonate system of the seawater and to a decrease in pH value, and thus to acidification of the ocean (Section 4.1.1; Turley et al., 2006). Without counteractive measures this change in the carbonate system could reach a state during this century that has probably not been seen for several million years (Feely et al., 2004). Humans are significantly interfering with the chemical balance of the ocean, and this will not remain without consequences for marine organisms and ecosystems.

4.3.1
Physiological effects on marine organisms

A strong increase of CO_2 concentration (hypercapnia) has many adverse physiological effects that have been investigated experimentally on various marine organisms. Numerous changes in marine organisms have been identified, for example, in the productivity of algae, metabolic rates of zooplankton and fish, oxygen supply of squid, reproduction in clams, nitrification by microorganisms, and the uptake of metals (for a survey, see Pörtner, 2005). Many of these experiments, however, were carried out with CO_2 concentrations much higher than what could be expected in emission scenarios under discussion today for the time frame up to 2100. Further studies are therefore necessary in order to be able to estimate the short- and medium-term effects of acidification (Section 4.6). From today's viewpoint it seems improbable that marine organisms will suffer from acute poisoning at expected future CO_2 levels (Pörtner, 2005).

Doubling the present CO_2 concentration leads to an increase in the rate of photosynthesis in many phytoplankton species by about 10 per cent (Raven et al., 2005). However, the various groups of phytoplankton exhibit different sensitivities to increased CO_2 concentrations with respect to photosynthesis, which is due to differences in carbon uptake (CO_2 versus HCO_3^-) and a different saturation behaviour of the photosynthetic rates. The interactions between photosynthesis, primary production of phytoplankton, microbial respiration, and the resulting effects on the food web are, however, compounded by a number of other factors (temperature, light and nutrient supply, disparate feeding risk from zooplankton, adaptive processes, etc.). With the present state of knowledge no clear conclusions can be drawn regarding the effects of acidification on growth rates and assemblage compositions of the phytoplankton.

4.3.2
Effects on calcifying organisms

Next to photosynthesis, calcification is the most important physiological process influenced by the increase of CO_2 concentration. It has far-reaching consequences for the ecological function of marine ecosystems, and can also have feedbacks on the atmospheric concentration of CO_2 and thus on the climate system (Section 4.3.5).

For their skeletons or shell structure, many marine organisms use calcium carbonate, which has to be extracted from seawater. This is only possible while the seawater is supersaturated with calcium carbonate, which is why the increasing CO_2 concentration and falling pH value hampers calcification (Raven et al., 2005). This causes a weakening of the skeletal structure or – when a level below the saturation concentration is reached – even their dissolution. Calcium carbonate is employed as a construction material for organisms in different crystalline forms: aragonite and calcite are the two most important (Table 4.3-1). Organisms that use aragonite for their shells or skeletons are the first to be adversely affected by acidification, because aragonite dissolves more easily under the changing conditions due to its different crystal structure.

Acidification has an impact on all marine calcifying species, such as certain plankton groups, clams, snails and corals. Echinoderms (for example, starfish and sea cucumbers) are especially threatened, because their calcite structures contain larger amounts of magnesium and therefore dissolve even more easily than aragonite under increased CO_2 conditions (Shirayama and Thornton, 2005). Although corals are the most conspicuous and well-known marine calcifying organisms and are especially threatened by acidification as aragonite producers (Section 2.4), they only contribute 10 per cent of the annual global marine carbonate production of 0.64–2Gt C (Zondervan et al., 2001). The simulations of Guinotte et al. (2003) indicate that at an atmospheric CO_2 concentration of just under 520ppm, which could already be reached by the middle of this century, almost all of today's warm-water coral reef locations will barely still be suitable for coral growth because of insufficient aragonite saturation (Fig. 4.3-1).

Around three-fourths of the global marine calcium carbonate production is carried out by planktonic organisms, primarily coccolithophores, foraminifera, and pteropods. Of these, the coccolithophores are of particular importance because these one-celled primary producers, which can create large-area plankton blooms with only a few species, can greatly contribute to the export of calcium carbonate to the deep sea and thereby play a significant role in the global carbon cycle (Riebesell et al., 2000; Zondervan et al., 2001; Section 4.3.5). In experiments with both monocultures and natural plankton communities it has been shown that the calcification by coccolithophores clearly decreases with increased atmospheric CO_2 concentrations (Riebesell et al., 2000; Riebesell, 2004). Pteropods are important components of the marine food webs in polar and subpolar latitudes where they form dense populations (up to 1000 individuals per m^3) and serve as nutrition for the upper trophic layers of the food web. In these regions they are responsible for a significant portion of the export of particulate carbon to greater depths. When the carbonate saturation in seawater drops below a critical value, it is likely that these animals are no longer able to form a shell. For important parts of their habitat in the Southern Ocean an undersaturation with respect to aragonite (under assumptions of the IS92 scenario of the IPCC) is predicted beginning in 2050, so that their distribution area will be severely limited (Orr et al., 2005; Raven et al., 2005).

There is great uncertainty about the capacity of the organisms to adapt to these changes, as too few long-term experiments have been carried out (Raven et al., 2005; Pörtner, 2005).

4.3.3
Ecosystem structure and higher trophic levels

Over the course of this century the expected pH decreases could have a considerable impact on the calcifying organisms and thus on the total marine biosphere (Orr et al., 2005). Simultaneously, considerable climate-related warming is expected. The two effects are not independent of one another: the CO_2 increase, for example, could decrease the temperature tolerance of animals (Pörtner, 2005). The coral ecosystems in particular are an example of such synergistic negative effects (Section 2.4; Hoegh-Guldberg, 2005).

Acidification impacts on the food web are also conceivable. Different responses to increased CO_2 concentrations, with respect to growth rates or reproduction of an organism, could change the spatial as well as temporal distributions of the species through changes in competition (Rost and Sültemeyer, 2003). Impacts that have already been observed in primary producers include a difference in the magnitude of the CO_2 fertilization effect (which, for example,

Organisms	Photosynthetic	Crystal form of the carbonate	Habitat
Coccolithophores	yes	Calcite	Planktonic
Macroalgae*	yes	Aragonite or calcite	Benthic
Foraminifera	no some	Calcite Calcite	Benthic Planktonic
Corals			
warm-water	yes (in symbiosis)	Aragonite	Benthic
cold-water	no	Aragonite	Benthic
Pteropods	no	Aragonite	Planktonic
Non-pteropod molluscs*	no	Aragonite or calcite	Benthic or planktonic
Echinoderms	no	Mg-calcite	Benthic
Crustaceans*	no	Calcite	Benthic or planktonic

Table 4.3-1
Groups of calcifying marine organisms. Calcium carbonate occurs in different crystal forms. Aragonite dissolves more quickly than calcite at low carbonate ion concentrations, but more slowly than magnesium-rich calcite (Mg-calcite).
* not all species of this group are calcifiers.
Source: after Raven et al., 2005

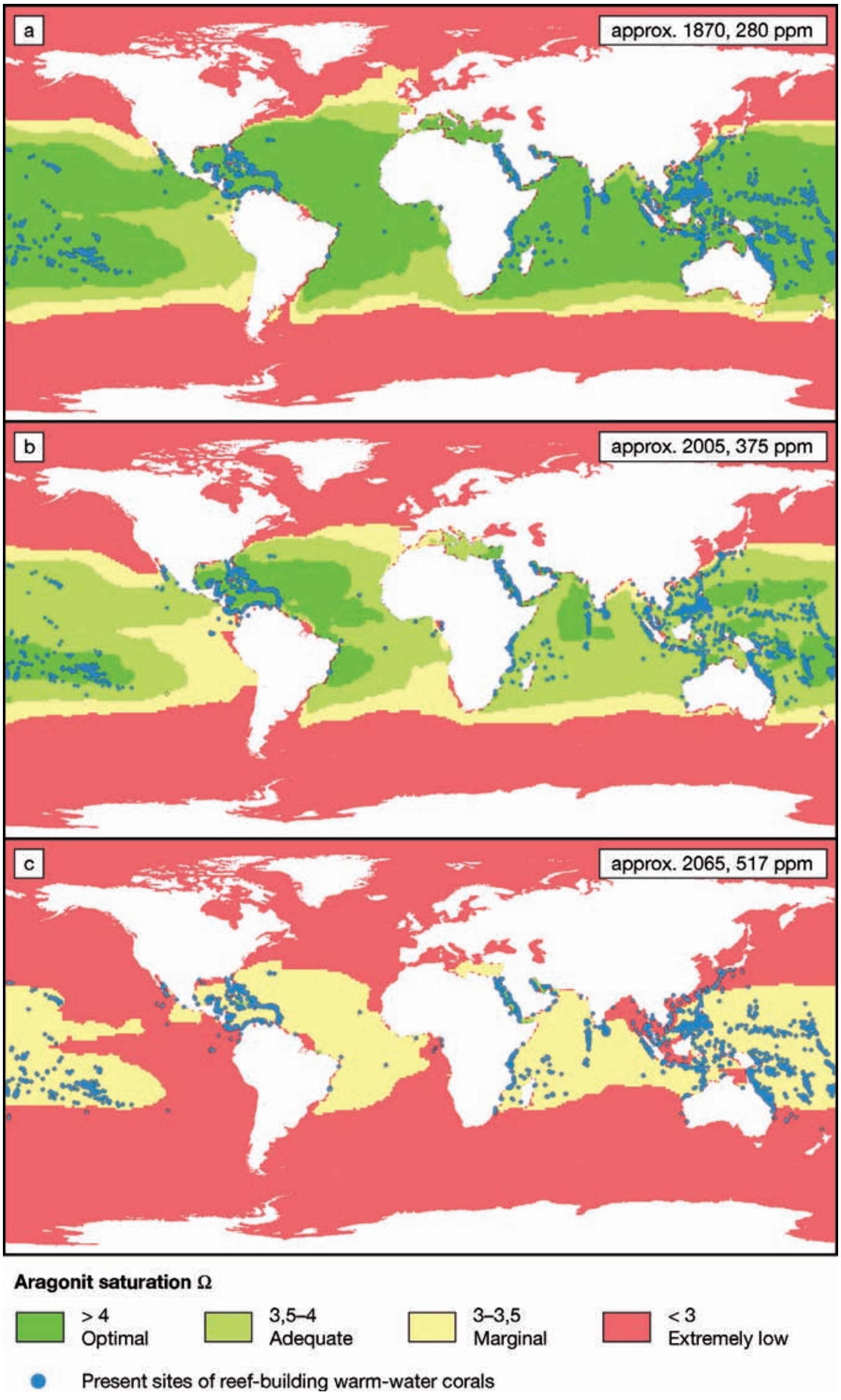


Figure 4.3-1
Aragonite saturation and present occurrence of reef locations for warm-water corals (blue dots). (a) pre-industrial values (around 1870, atmospheric CO_2 concentration 280ppm), (b) present (around 2005, 375ppm CO_2), (c) future (around 2065, 517ppm CO_2). The degree of aragonite saturation (Ω) indicates the relative proportion between the product of the concentrations of calcium and carbonate ions and the solubility product for aragonite. Locations with an aragonite saturation below 3.5 are only marginally suitable for reef-forming warm-water corals, below 3 they are not suitable.
Source: Steffen et al., 2004

favours coccolithophores over siliceous algae) and reduced calcification (which may be a disadvantage for coccolithophores: Riebesell, 2004). In long-term studies in the North Atlantic, it has been observed that changes in the phytoplankton, due to the close coupling with their predators, can be passed on first to the algae-feeding zooplankton and then further to the predatory zooplankton (Richardson and Schoeman, 2004). A change in the species composition of the phytoplankton can thus impact on the zooplankton. In polar ecosystems it is conceivable that reduced calcification by pteropods has effects on the higher levels of the food web, although this is speculative and not easily predictable (Orr et al., 2005).

Conclusions about possible adaptive processes at the ecosystem-structure level are also speculative, for example, whether gaps that are created by acidification impacts can be filled by other species without significant effects upon overall productivity.

4.3.4 Effects of acidification on fisheries

Acidification of the world's oceans could also have an impact on fisheries. Direct toxic effects of increased atmospheric CO_2 concentrations on fish are not expected because the threshold of acute sensitivity of fish to CO_2 is beyond the predicted concentrations (Pörtner, 2005; Section 4.3.1). When calcification is reduced, however, this can trigger changes in the species composition of the phytoplankton, and this, in turn, can have an impact all the way to the upper layers of the food web through trophic coupling (Richardson and Schoeman, 2004; Section 4.3.3). It cannot be ruled out that this kind of change in the structure and function of the marine ecosystems can have an impact on the pelagic fisheries, but with the present state of knowledge the prognosis remains very speculative (Raven et al., 2005).

Changes in growth and competitive conditions for the species in tropical coral reefs will probably also affect another important branch of fishery: millions of people depend on subsistence fishery on coral reefs for their protein supply (Raven, et al., 2005), and the coral reefs themselves are threatened by acidification (Section 2.4). A large-scale loss of coral habitats would doubtless have adverse effects upon this fishery, with socioeconomic consequences that are difficult to predict.

4.3.5 Feedback of changes in calcification on the carbon cycle

Overall, the ecological balances in the sea are shifting to the detriment of calcifying organisms, and this may affect even the global biogeochemical cycles through changes in species compositions in marine phytoplankton. The consequences of changing rates of plankton calcification described here represent only a small sample of all the interactions between the climate system and the ocean, which are reviewed in Section 4.2.

The annual primary production in the ocean is approximately 50Gt C, of which approximately 10Gt is exported to the deep sea by the biological pump. For this important process in the global carbon cycle, which contributes to the sink function of the ocean, it makes a great difference whether the production is by calcifying species like coccolithophores or by non-calcifying species, for example, siliceous algae.

Calcification by marine organisms always involves CO_2 production:

$$Ca^{2+} + 2\,HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$$

This carbonate 'counter-pump' becomes stronger with increasing atmospheric CO_2 concentration as a consequence of the altered carbonate buffer capacity. Assuming constant calcification, this would cause a future weakening of the sink effect of the sea. But if biogenic carbonate formation is reduced as a result of a pH decrease, then this effect can be overcompensated so that the sink effect may even be strengthened. This would, however, only have a minor impact on the CO_2 uptake by the ocean (Zondervan et al., 2001). A number of other effects further complicate this picture (Riebesell, 2004): reduced calcification could also reduce the density and thus the sinking rates of particles to the deeper water layers, slowing the carbon export by the biological pump. On the other hand, there is a possible acceleration of the sinking rates caused by the increased formation of extracellular polysaccharides (Engel et al., 2004). Present-day plankton blooms of coccolithophores cover large areas of the sea, up to hundreds of thousands of km^2, and lighten the colour of the water because of their carbonate content. Their absence could therefore reduce the global albedo by up to 0.13 per cent, which would slightly accelerate global warming (Tyrell et al., 1999). The magnitude of some of these factors is not clear. The total effect of all of these factors on the interactions between atmospheric CO_2 concentration and marine biological production cannot currently be ascertained, which presents a need for increased research efforts in this area (Raven et al., 2005; IMBER, 2005).

4.4 Guard rail: Ocean acidification

4.4.1 Proposed guard rail

To prevent undesirable or high-risk changes to the marine food web due to aragonite undersaturation (Section 4.3), the pH value of near surface waters should not drop more than 0.2 units below the pre-industrial average value of 8.18 in any larger ocean region (nor in the global mean). A pH drop of 0.2 units would correspond to an increase in the H^+ ion concentration of around 60 per cent compared to pre-industrial values. The decrease in pH so far of 0.11 units since industrialization corresponds to a rise of the H^+ ion concentration of around 30 per cent. The present average pH value of the ocean surface layer is 8.07 (Raven et al., 2005). Figure 4.4-1 illustrates the WBGU acidification guard rail.

It is necessary, however, to further specify the spatial and temporal averaging to which the guard rail refers, because the pH value is subject to strong natural variability. According to Haugan and Drange (1996), pH values vary up to 0.5 units worldwide, while local seasonal fluctuations can amount to around 0.1 pH units (in high-production regions even 0.2–0.3 units: Riebesell, personal communication).

According to simulations by Caldeira and Wickett (2005), a stabilization of the atmospheric CO_2 concentration of 540ppm by the year 2100 would already lead to a pH decrease of the ocean surface layer of 0.23 in the global average compared to the pre-industrial level, that is, at this CO_2 concentration the acidification guard rail would already be overstepped. A stabilization at 450ppm by 2100 reduces the pH value by 0.17, and so would presumably be consistent with the acidification guard rail. It still needs to be reviewed, however, whether at this stabilization value higher pH reductions could occur locally over longer time periods, which, especially in the Southern Ocean, could lead to undersaturation of the surface layer with respect to aragonite. It should be noted that this refers to the stabilization of CO_2 itself and not the stabilization level of greenhouse gases in total, which is described by the CO_2 equivalent.

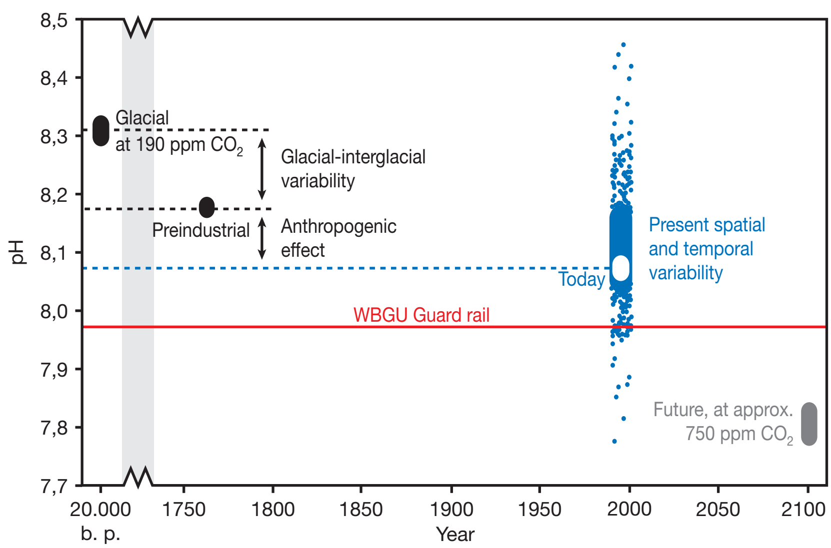
4.4.2 Rationale and feasibility

The largest threat to marine organisms due to acidification is related to the solubility of calcium carbonate, which they need for the construction of their shells and skeletal structure (Section 4.3). The more easily dissolved variant of calcium carbonate is aragonite, which is used by corals and certain plankton species (Table 4.3-1). Calcifying marine organisms are important components of marine ecosystems, so their endangerment would represent a non-tolerable interference with the Earth System.

If the concentration of carbonate ions falls below the critical value of 66μmol per kilogram, then the seawater is no longer saturated with respect to aragonite, and marine organisms can no longer build their aragonite shells. This needs to be avoided above all in the surface layer where primary production takes place. The danger of undersaturation for aragonite is especially present in the Southern Ocean. According to Orr et al. (2005), simulations where the pH decrease averages about 0.25 already show a clear reduction of the vertical extent of the saturated layer, and undersaturation in some parts of the Southern Ocean. It is the view of WBGU that such a situation should be avoided.

The pH value is a critical variable not only for calcification, but also for many other processes in marine systems (for example, availability of nutrients). Within the past 23 million years the natural fluctuations of the average pH value between glacial and interglacial periods lay within a range of slightly more than 0.1 (Fig. 4.4-1), so that over a long time marine organisms were able to adapt to a fairly nar-

Figure 4.4-1
Variability of the average pH value of the oceans in the past and present, as well as a projection for the future for an atmospheric CO_2 concentration of approx. 750ppm. The red line indicates the WBGU guard rail.
Source: after IMBER, 2005



row pH span that very rarely dropped below the minimum in the surface-layer water (IMBER, 2005). This is a further argument for application of the precautionary principle, especially considering the gaps in the scientific knowledge about the impacts of acidification (Section 4.3).

Because of the importance of the consequences of ocean acidification, research in this area should be intensified considerably (Section 4.6). As long as there is no general scientific consensus about the tolerable limit for the effects of acidification, a margin of safety according to the precautionary principle should be observed. The suggestion of WBGU to prevent a pH decrease of more than 0.2 is oriented toward the goal of avoiding an aragonite undersaturation in the ocean surface layer. If it is found that other intolerable damages already occur before reaching aragonite undersaturation, then the guard rail will have to be adjusted accordingly.

Because the CO_2 input into the sea is caused by a rise in atmospheric CO_2 concentrations and therefore by anthropogenic CO_2 emissions, the pH drop in the ocean can be limited by reducing emissions. Once acidification has occurred, however, it is irreversible – as long as there is no possibility of lowering the atmospheric CO_2 concentration the pH value of the surface layer will not rise again in any foreseeable future. Overstepping the guard rail would thus be irreversible, which makes the precautionary principle particularly relevant to this problem.

Compliance with the guard rail can be verified reliably by scientific means: for one, the pH value of seawater can be determined directly, and for another, the average pH value of the sea can be derived from measurements of atmospheric CO_2 concentrations.

The acidification and climate guard rails could exhibit redundancies with regard to the measures required to obey them, but they are not replaceable by one another: human-induced global warming is caused by a group of greenhouse gases, with 60 per cent of the effect from CO_2. The only one of this group responsible for ocean acidification, however, is CO_2. Stabilization of CO_2 at 450ppm by 2100 would reduce the pH value by 0.17, therefore staying within the allowable range of the acidification guard rail. Compliance with the global warming guard rail of 2°C also requires a stabilization concentration of 450ppm or less, depending on climate sensitivity. Therefore, observance of the climate guard rail would incorporate the acidification guard rail, under the condition that CO_2 is adequately taken into account in the emissions reduction.

4.5 Recommendations for action: Linking climate protection with marine conservation

In the 1970s and 1980s, the phenomenon of 'acid rain' became widely known. This problem is caused by emissions of acid-forming gases (mainly SO_2 and NO_X) from the combustion of fossil fuels. The issue was taken up by the media under the catchphrase 'Waldsterben' (forest dieback), and exerted considerable pressure upon policymakers and industry. Great technical and financial effort was subsequently invested to fit large-scale power plants with flue gas scrubbers, mandate catalytic converters for cars, and embark upon broad-scale liming of forests and lakes. A comparison of the problem of acid rain with the already advancing acidification of the oceans shows the latter to be an issue significantly more serious. The media and policymakers, however, are expressing negligible interest compared to acid rain. Indeed, the problem is being practically ignored. Policymakers are therefore called upon to recognize the full impact of ocean acidification and to take measures of a scope and effectiveness comparable to those adopted to tackle acid rain.

4.5.1 Reappraising the role of CO_2 in climate protection policy

The release of CO_2 has particularly far-reaching consequences for marine ecosystems. Firstly, CO_2 acts as a greenhouse gas, altering the radiation balance of the atmosphere and thus contributing to global atmospheric warming and, as a further consequence, to the warming of the oceans. Secondly, a large proportion of the CO_2 emitted by human activities dissolves in seawater, where, in addition to the warming, it causes chemical changes. In view of these particularly harmful effects of CO_2 upon the oceans, it is essential that climate policy give special attention to this specific greenhouse gas.

Need for action

Compliance with the WBGU guard rail for ocean acidification will only be possible if the increase of the atmospheric CO_2 concentration is limited. Engineering approaches, such as liming the surface layers of the oceans, are unrealistic considering the scale of the problem (Raven et al., 2005). However, over a time scale of centuries, the acidified surface water will mix down into the deep sea through ocean currents. One option for action is to stabilize the atmospheric CO_2 concentration; this would lead over the long term to an acidification of deeper waters of the oceans until the pH of the surface layers is reached. An alternative option would be to agree a maximum limit on the total amount of CO_2 emitted to the atmosphere by human activities; that approach could cause the atmospheric CO_2 concentration to drop again over the medium term and could prevent the acidification of the deep sea.

Legal setting

The present climate policy instruments do not take into account the aspect of ocean acidification caused by CO_2 input. WBGU takes the view that the United Nations Framework Convention on Climate Change (UNFCCC) does indeed establish an obligation to take into account the impacts of climate change upon the oceans, regardless of the circumstance that this aspect was not a priority when the UNFCCC was concluded, and was not covered by the Kyoto Protocol when reduction commitments were set. The rationale is as follows: Under Art. 1 para. 3 UNFCCC, 'climate system' means the totality of the atmosphere, hydrosphere, biosphere and geosphere and their interactions. The term 'climate system' is thus defined in such a comprehensive way that it includes the oceans, which are a part of the hydrosphere, as well as the interactions of the oceans with the atmosphere and the biosphere. The UNFCCC objective established in Art. 2, 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system', thus also covers the impacts of increasing greenhouse gas levels upon the oceans. With respect to acidification, the meaning of Art. 2 UNFCCC can be concretized as follows: CO_2 is a greenhouse gas, and an excessive CO_2 concentration in the atmosphere leads to dangerous anthropogenic interference with marine ecosystems, for CO_2 dissolves in water and causes acidification (Sections 4.1 and 4.3). The oceans are a part of the hydrosphere, and marine organisms are a component of the biosphere. The problem of acidification is thus one of interaction among the atmosphere, hydrosphere and biosphere, all of which are components of the climate system (Art. 1 para. 3 UNFCCC). There can thus be no doubt that the objectives of the convention include preventing a dangerous acidification of the oceans. Furthermore, Art. 2 UNFCCC also states that ecosystems should be able to adapt naturally to climate change. The speed of acidification observed today calls compliance with this requirement into question: for instance, the adaptive capacity of marine ecosystems can be overstretched if the aragonite saturation horizons in the Southern Ocean rise to the surface (Section 4.3). This presents an immediate need to limit acidification and adopt appropriate measures under the UNFCCC.

Recommendations

WBGU argues against this backdrop that climate policy needs to take all impacts upon the marine habitat into account. In the negotiations on the second commitment period under the Kyoto Protocol now commencing, the German federal government should work to ensure that the direct adverse effects of CO_2 emissions upon the oceans are taken into account. The desired stabilization of atmospheric greenhouse gas concentrations should be set in such a way that ocean acidification is adequately limited. This implies that CO_2 should not be viewed only as part of a basket of various greenhouse gases. The atmospheric CO_2 concentration rather needs to be stabilized specifically, regardless of the reduction of other greenhouse gases – at a level permitting compliance with the WBGU acidification guard rail (Section 4.4).

To achieve this goal, it may be necessary to define a CO_2 emissions ceiling for individual states or groups of states in addition to existing reduction commitments. This CO_2 cap would then need to be observed as a complement to the other commitments. The precise effects of this and any further potential instruments still need to be clarified. A particularly important aspect in this regard is the possible need for adaptation of the existing flexible mechanisms (emissions trading, Clean Development Mechanism and Joint Implementation).

It would not, however, be necessary to define a separate ceiling for CO_2 if, firstly, the international community were to agree to reduce greenhouse gas emissions to a level ensuring compliance with the WBGU guard rail on climate protection, and, secondly, the relative proportion of CO_2 within overall greenhouse gas emissions does not change significantly. The CO_2 reduction needed in this case would most probably suffice to prevent transgression of the acidification guard rail.

4.5.2
Taking shipping sector emissions into account

As a part of efforts to stabilize the atmospheric CO_2 concentration, the CO_2 emissions generated by ocean shipping and international aviation should be integrated more closely into emissions reduction strategies. No quantitative reduction commitments have yet been agreed for either sector. WBGU recommends closing these regulatory gaps by integrating the CO_2 emissions generated by international shipping and aviation into negotiations on future reduction commitments within the Kyoto process. Present estimates suggest that worldwide CO_2 emissions from shipping amount to about 2 per cent of global emissions. Over the past decade, the rate of increase in shipping emissions was more than twice that for total emissions (Bode et al., 2002; IEA, 2002). This illustrates the urgent need for action.

Besides emitting CO_2, ocean shipping also generates pressures upon marine and coastal ecosystems by emitting pollutants, nutrients and sediment particles. Controls on ocean shipping thus present a starting point for linking climate protection with marine conservation at the level of legal instruments.

In view of the relatively good environmental performance and significant economic importance of ocean shipping, regulatory controls need not aim to reduce the volume of shipping traffic. The goal is rather to create incentives for technological innovations and improvements in environmental management that contribute both to abating ocean pollution and preventing atmospheric CO_2 emissions. As a means to this end, WBGU recommends levying charges on the use of the oceans by shipping (WBGU, 2002).

This instrument highlights the connection between the utilization of the environmental resources represented by 'the oceans' and 'the atmosphere' and the utilization-related impairment of these resources. A charge signals the scarcity of environmental resources and the cost of their provision. The economic players burdened by a charge receive an incentive to modify their utilization of global environmental goods and to make it more sustainable (WBGU, 2002).

WBGU has set out the options for designing a user charge system in detail elsewhere (WBGU, 2002). A proposed user charge regime applied to the European Union area alone could generate annual revenues of € 400–700 million. WBGU proposes that the financial resources thus received be earmarked for marine conservation purposes, in order to create a substantive link between the generation and reduction of pressures upon the oceans (WBGU, 2002).

4.6 Research recommendations

Acidification and marine ecosystems

The physiological effects of acidification on marine organisms, especially on calcifying ones, and the impacts on the marine ecosystem are insufficiently understood. Physiological experiments are needed with moderately increased CO_2 concentrations, as are experiments exploring the effects on marine food webs (trophic coupling among phytoplankton, zooplankton and fish), and studies of possible physiological adaptation processes on an evolutionary basis.

Biogenic calcification and the carbon cycle

Our understanding of the interactions between calcifying plankton, the biological pump, and the global carbon cycle shows similar gaps, so modelling of the net effect is not yet possible. Modelling studies therefore need to be carried out on the acidification-related reduction of biological export production due to decreased mineral ballast (carbonate shells).

Further impacts of climate change

Acidification is probably just one of many changes that will take place in the biogeochemistry of the oceans due to anthropogenic greenhouse gas emissions, or through climate change. Other aspects, such as the effects on oxygen balance and nutrient supply in the sea, are poorly understood and urgently need further study in order to recognize critical developments in good time.

Future CO_2 uptake by the ocean

CO_2 uptake by the ocean plays a key role in climate change. Interactions among the atmospheric radiation balance, the chemical composition of the atmosphere and the physical, chemical, and biological changes in the ocean should therefore receive increasing attention.

International research programmes

Promotion of projects by international research programmes (e.g., SOLAS, 2004; IMBER, 2005) that address the questions above is recommended.

CO_2 and climate protection

In the event that a specific reduction commitment for CO_2 proves to be necessary, the potential ways of designing such a commitment need to be developed and evaluated. In addition, the implications for Kyoto mechanisms (especially CDM and emissions trading) need investigation.

CO_2 storage in the ocean and under the sea floor 5

Great and growing hopes have been pinned of late upon the sequestration of CO_2 as a means of climate mitigation (IEA, 2004). IPCC discussed this theme in depth in a recent Special Report (IPCC, 2005). Estimates expect carbon dioxide capture and storage (CCS) to be market-ready by 2015 (IEA, 2004). Within 50 years, 20–40 per cent of the CO_2 emissions arising from the combustion of fossil fuels could be separated, captured and stored (IPCC, 2005), provided that research and development intensify significantly (IEA, 2004). Sequestration technology has direct relevance to the present report, as it also includes the storage of CO_2 in the ocean and under the sea floor (Box 5.3-1).

5.1 CO_2 sequestration

5.1.1 Potential and costs

The technology of carbon dioxide sequestration has three components: CO_2 capture, transport and storage (IEA, 2004). Storage locations under consideration include sub-seabed geological formations, the water column of the ocean, and onshore geological formations such as depleted oil and gas fields and unminable coal seams. Chemical fixation to metal oxides is conceivable, although this process is currently regarded as unsuitable in view of the enormous energy consumption and very high costs associated with it (IPCC, 2005).

The storage capacity of depleted oil and gas fields is approximately 30 to 40 times the current annual CO_2 emissions from the combustion of fossil energy carriers. The storage potential through Enhanced Oil Recovery (EOR), whereby CO_2 is injected into cavities in order to increase oil yield, is estimated as 3 to 5 times the annual CO_2 emissions. Estimates for absorption in coal seams vary between 13 per cent and nine times annual CO_2 emissions. Saline aquifers under the sea may be able to hold 40 times the annual CO_2 emissions or more (IPCC, 2005). However, with the exception of EOR, little practical experience relating to geological storage is available, and the suitability of potential reservoirs is not clear.

Large point sources such as large fossil power plants near potential storage locations are regarded as particularly attractive for CCS. Typically, 80–90 per cent of the CO_2 generated in fossil power plants could be captured. However, the process requires energy, resulting in an increase in fuel consumption by 16–31 per cent (or even 70 per cent if the technology is retrofitted to existing lignite-fired power plants). Transportation and injection of CO_2 require comparatively small amounts of energy. Compared to the amount of emissions avoided, about 20–40 per cent more CO_2 has to be put into storage – and more than twice the amount if existing lignite-fired power plants are retrofitted.

CO_2 emissions from large-scale biomass facilities would also be suitable for sequestration. This would create an actual CO_2 sink, since the carbon contained in the biomass was previously removed from the atmosphere via photosynthesis.

The costs of CO_2 capture are currently estimated at US$11–57 per t of CO_2, depending on the fuel, the age and type of the power plant, and the capture technology used (IPCC, 2005). Pipelines are state of the art for CO_2 transportation. In the USA alone, 40Mt CO_2 are transported each year via pipelines with an overall length of 2500km. However, for large distances transport by ship is more economic than pipelines. The costs for transporting 1 tonne of CO_2 by ship are approximately US$15–25 per 5000km, compared with US$4–30 per 1000km via pipelines (IEA, 2004; IPCC, 2005). The costs for injection and storage are comparatively low, estimated at US$0.5–8 per t of CO_2. In addition, there are minor costs for monitoring and maintenance of the reservoirs. The total costs of sequestration involving storage in the ocean or under the sea floor therefore range between US$20 and 100 per t of CO_2.

Based on current knowledge, sequestration of the CO_2 released during power generation would lead to increases in generating costs per MWh amounting to

US$12–34 in new power plants. For retrofitted lignite-fired power stations the cost increase is estimated at US$33–44 per MWh (IPCC, 2005). Current generating costs are around US$25–55 per MWh, depending mostly on fuel prices, which means that total generating costs including sequestration would be US$45–80 per MWh. This range is comparable with many wind and small-scale hydroelectric plants (Box 5.3-2). Sequestration would increase power generation costs in fossil power plants by 30–60 per cent for new plants. Retrofitting existing plants may triple costs. Optimistic forecasts assume that sequestration costs are likely to come down significantly by 2030. However, based on renewable electricity generating costs of US$10–20 per MWh (IEA, 2004) and expected increases in fossil fuel prices in the long term, electricity generation from renewables is likely to become an increasingly cost-effective option.

5.1.2 Risks and sustainability

The uncertainty regarding the environmental sustainability of sequestration is more significant than the uncertainties relating to cost development. A distinction has to be made between three types of risk.

1. *Risk of accidents:* Similar to natural gas pipelines, CO_2 pipelines may be affected by leakage. CO_2 concentrations of more than 7–10 per cent in air endanger health and life. However, experience with existing pipeline systems shows that major damage to pipelines is very rare. In addition, the risk can be reduced further through improved pipeline design and monitoring. Sudden escape of large quantities of CO_2 is also conceivable during CO_2 injection into the repository. In addition, similar to EOR or natural gas storage, stored CO_2 may escape abruptly, e.g. due to inadequate sealing of the repository (IPCC, 2005). However, this type of major accident is regarded as unlikely in conjunction with CO_2 storage. The immediate impacts of such an incident would be significantly lower at sea than in inhabited areas, where severe, in extreme cases fatal impact on humans would have to be expected.
2. *Potential impact on marine ecology:* This is mainly associated with CO_2 disposal in seawater, which WBGU regards as unacceptable. The issue is discussed in Section 5.2.
3. *Continuous slow escape of stored CO_2:* This risk is highly significant in the context of long-term climate change mitigation. While the IPCC Special Report (IPCC, 2005) contains no specific data on acceptable leakage rates, a simple rough calculation can provide some guidance. The cumulative emissions in the different SRES scenarios for 1990–2100 vary between 1000Gt C (B1 scenario) and 2200Gt C (A1FI scenario) (IPCC, 2000). In order to comply with the 2ºC climate guard rail, the cumulative emissions to the atmosphere from the present need to be limited to 500Gt C (Meinshausen, 2006). Compared with a medium-level scenario assuming emission of 1500Gt C by 2100, around 1000Gt C would have to be mitigated. If this quantity were to be sequestered, with a leakage rate of 0.1 per cent per year (i.e. a retention period of 1000 years) 1Gt C would escape uncontrolled every year. However, in order to comply with the 2ºC guard rail, a maximum of 1Gt C of total emissions per year would be acceptable in the long term (from about 2200), even for the case assuming an average climate sensitivity of 3ºC (Caldeira et al., 2003). Thus even assuming a medium-level emissions scenario, which does not represent the worst case, leakage from CO_2 storage sites alone would represent 100 per cent of admissible CO_2 emissions in the long term. The situation is even more problematic if less optimistic assumptions are made: Climate sensitivity may prove to be higher, other greenhouse gases (e.g. methane, see Chapter 6) may contribute to warming more strongly than assumed, or the proposed 2ºC guard rail may prove to be too high in the long term, e.g. in the event that it triggers the melting of Greenland ice (see Chapter 3). Overall, no more than one-tenth of the above-mentioned leakage rate would therefore appear to be acceptable, i.e. 0.01 per cent per year, corresponding to a retention period of 10,000 years. Therefore, sequestration can only be regarded as an acceptable climate mitigation technology if long-term CO_2 storage for at least 10,000 years can be guaranteed.

5.2 Ocean storage

Two basic options are under consideration for carbon sequestration in the ocean: physical-chemical dissolution in the seawater and, in the broadest sense, biological-engineered storage in marine ecosystems, primarily through iron fertilization. In the following, only the physical-chemical techniques will be discussed in detail. This report does not explore the concept of using permanent input of iron to trigger algal blooms and thereby increase the sink potential of the ocean in marine areas where the micro-nutrient iron is the limiting factor for primary production (notably the Southern Ocean). The expected quantitative effect is fairly low (as a comparison with palaeoclimatological data leads one to presume), and there is doubt that the permanence of storage is sufficient (Section 5.1.2). Furthermore, the risks of large-scale iron fertilization in terms of indirect effects on the marine ecosystem are hard to estimate. WBGU has already explained elsewhere the reasons for its rejection of iron fertilization of the ocean (WBGU, 2004).

5.2.1 Storage and residence time of CO_2

Direct injection into seawater is one form of CO_2 storage that is under discussion. The CO_2 content of the sea surface equilibrates relatively quickly with the atmosphere, so that an artificial increase of CO_2 in the surface water would result in outgassing to the atmosphere within a short time. Introduction into the deep sea could, in contrast, ensure a longer residence time of carbon in the sea. The CO_2 injected there could remain isolated from the atmosphere for several centuries (IPCC, 2005), but over longer time periods the equilibrium between atmospheric CO_2 concentration and that in the sea would be re-established. Then, depending on the atmospheric CO_2 concentration, between 65 and 80 per cent of anthropogenic CO_2 would be stored in the sea, regardless of whether the CO_2 has been emitted to the atmosphere or injected into the ocean (Caldeira et al., 2005). The injection of CO_2 into seawater could thus reduce a peak concentration of CO_2 in the atmosphere, but it has no influence on the long-term stabilization level of atmospheric CO_2. Thus, independent of the consequences for the marine ecology (Section 5.2.2), it does not represent a sustainable solution for the problem because future generations would be burdened with irreversible effects.

Another technological option would be the storage of CO_2 as a liquid or hydrate on the sea floor, which would only be possible in water depths below 3000m due to its greater density there. Without a physical barrier, however, the CO_2 would slowly dissolve from such reservoirs into the overlying water column. So this technology would also only lead to a postponement of the consequences of climate change, but not to their mitigation. None of the technological possibilities being discussed for storage in seawater have been tested in field studies at a meaningful scale. Approval has not been given for any of the research projects so far proposed, not even for injecting just a few tonnes of carbon dioxide into the deep sea.

5.2.2 Impacts of CO_2 storage on deep-sea organisms

Just as in the surface layer, the direct injection of CO_2 into the deep sea also changes the chemical and physical characteristics of the seawater. Initially this affects the direct surroundings of the location of introduction, for example, the end of the pipeline through which the liquid CO_2 flows into the deep sea. Here, as simulations indicate, dramatic changes in the local pH values of up to several units can occur. Through technical solutions that lead to faster dilution (such as a pipeline towed by a ship), the maximum local pH change can be reduced. In the somewhat broader surroundings (several kilometres), the rate of dilution is essentially determined by ocean currents, so that the chemical and physical impacts can be estimated with ocean circulation models. For example, with an input of 0.1Gt C per year (which is less than 2 per cent of the industrial emissions and around 5 per cent of the present CO_2 input through the sea surface caused by anthropogenic CO_2 level rise in the atmosphere), in up to 0.01 per cent of the ocean volume the pH value could drop by 0.3 units over a period of 100 years (Caldeira et al., 2005). CO_2 storage in the deep sea could thus have serious impacts on the deep-sea ecosystem. Deep-sea organisms develop very slowly, their metabolic rates are lower and life expectancy is greater than of organisms in other ocean layers (IPCC, 2005). During their evolution, the inhabitants of the deep-sea ecosystem have adapted to special living conditions, with typically very stable temperatures and pressures, and relatively constant CO_2 concentrations (except at volcanic CO_2 vents). Such constant environmental variables do not demand rapid adaptive strategies. Thus, it has to be expected for the possible storage of CO_2 on the sea floor, as well as for leakage of a storage reservoir below the sea floor, that the ecosystem affected will be critically damaged, or will take a long time to recover from a change in the environment (IPCC, 2005).

Very little is known about the organisms in the deep sea in general, their life forms and interactions. So far, the direct effect of CO_2 on marine organisms has mainly been investigated in the laboratory. Studies involving field observations are greatly lacking, except for a few experiments with small CO_2 plumes on the sea floor and investigations of volcanic CO_2 vents (Pörtner, 2005).

In one of these in-situ experiments off the coast of California, liquid CO_2 was injected at 3600m in order to study the survival and behaviour of the deep-sea fauna after direct contact with CO_2 (Barry et al., 2004). Depending on pH changes and distance from the CO_2 plume, the survival rate of the animals varied. Flagellates, amoebas and nematodes in the sediment zone near the CO_2 source showed a high mortality. In another study, the scents of prey animals were combined with the extrusion of CO_2 (Tamburri et al., 2000). Fish and invertebrates were attracted by the scents and appeared to some extent to remain relatively undamaged, even at a distance of just a few centimetres from the CO_2 source, in spite of the low pH value. Carrion-eating hagfish, attracted by the scent of the prey, did not seek to escape narcotization under the high CO_2 content. Tyler (2003) therefore fears that animals that die through contact with CO_2 introduced into the deep sea could attract larger carrion eaters, who would then likewise be killed by the CO_2 plume. Squid and other invertebrates may react more sensitively to high CO_2 concentrations than vertebrates (Pörtner et al., 2004) because their body fluids contain no haemoglobin, which helps protect the body from large pH fluctuations. So even a small, local CO_2 plume could have wide-reaching effects on its surroundings.

Risks also arise from outgassing into the atmosphere. Two catastrophes occurred in the 1980s when large CO_2 plumes from gas-saturated deep water escaped into the atmosphere from the volcanic Lakes Monoun and Nyos in Cameroon. The disaster at Lake Nyos had devastating consequences: around 80 million m^3 of CO_2 were expelled, taking the lives of at least 1700 people and several thousand animals up to a distance of 10km from the lake (Kling et al., 1987; Clarke, 2001). There is sparse information in the literature on whether Lake Nyos harboured life of any kind before the catastrophe, and how the gas plume affected this biotope. Freeth (1987) has reported that, in spite of otherwise favourable living conditions, the local population had neither seen fish in the lake before the catastrophe, nor were fish cadavers found after the event.

If a large plume of CO_2 pumped into the sea should rise to the sea surface or into higher water layers, the possible ecological results can only be speculated. In summary, the largely incalculable ecological risks also support a general prohibition of CO_2 storage in seawater.

5.2.3 Present international law

The relevant body of international law relating to CO_2 storage in the ocean and below the sea floor can be summarized as follows: according to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter – the London Convention of 1972 – the disposal of certain wastes and other matter (listed in Annex I to the convention) into the sea is forbidden. Further wastes and matter listed in Annex II to the convention may only be disposed of with prior special permission. Other wastes and matter may be disposed of under a prior 'general' permit. Since 1 January 1996, the 'black list' of Annex I includes industrial waste (No. 11), which means 'waste materials generated by manufacturing or processing operations'. It can be assumed that separated CO_2 is derived from such operations and is therefore industrial waste within the meaning of Annex I. However, with respect to matter whose discharge into the ocean is prohibited, the convention contains an important exception in connection with the extraction of mineral resources: according to Art. III, para. 1(c) of the London Convention, the 'disposal of wastes or other matter directly arising from, or related to the exploration, exploitation and associated offshore processing of seabed mineral resources' is not covered by the provisions of the convention. In other words, the disposal of CO_2 that is generated by the production of oil or natural gas at sea is permitted under the Convention, as long as the corresponding processing operations are carried out at sea.

Basically the same legal position exists under the Protocol of 1996, although the approach is different: the Protocol, which will replace the Convention in the future but has not yet been ratified by a sufficient number of signatories and is therefore not yet in force, contains a general prohibition of discharge into the sea, combined with a list (Annex 1) of exceptions. CO_2 is not included among these exceptions. This means that the discharge of CO_2 would be essentially prohibited under the Protocol once it enters into force. But, according to the Protocol, the discharge would still be allowed when the CO_2 is derived from the recovery of oil or natural gas at sea and the processing also takes place there (Art. 1, para. 4.3).

5.3 Sub-seabed geological storage

5.3.1 CO_2 injection into the geological sub-seabed

Injecting CO_2 into geological formations below the sea floor is basically no different than the procedure on land. Saline aquifers, for example, also provide repositories, and pressurized injection of CO_2 into oil formations could facilitate the extraction of oil. The technical systems just have to be adapted for the existing conditions. The appropriate monitoring techniques, however, are very different on land and in the sea. There are also some differences with respect to safety technology (Section 5.3.3.4).

Not only are great research efforts presently being carried out on CO_2 storage in the seabed (CSLF, 2005), but practical experience already exists in this field, and further projects are planned (Bellona Foundation, 2005; Deutsche BP, 2005). When charges on CO_2 or the prices for emission rights rise, sequestration becomes more economically attractive, and companies can be expected to apply increasing efforts in addition to the Sleipner project (Box 5.3-1) and EOR (Section 5.1). The Norwegian company Statoil is already considering the transport of 'foreign' CO_2 through pipelines to the company's Sleipner gas platform, and storing it there in the CO_2 formations already in use under the sea.

5.3.2 Risks and sustainability of CO_2 storage in the seabed

Various scenarios are imaginable for the escape of CO_2 from formations under the sea floor. If the CO_2 emerges at a depth where it occurs as hydrate, then the least damage can be expected. But when the CO_2 dissolves in water it contributes to acidification of the sea. The conceivable harmful consequences of leaks for marine organisms have already been described in Section 5.2.2. In cases of very large-volume leaks, the CO_2 could also reach the surface, which would, for one, contribute to the enrichment of CO_2 in the atmosphere and, for another, present a health risk in the immediate surroundings. But as long as the storage site is not directly on the coast near human settlements, the human health risk is significantly lower

Box 5.3-1

The Sleipner project

The Sleipner Platform in the North Sea is located approximately 250km from the coast of Norway. It is the first commercial project for CO_2 storage in a saline aquifer under the sea floor. CO_2 separated from natural gas here is transported locally to a depth 800m below the sea floor. The storage of CO_2 here is economically interesting because the separation of CO_2 from the gas is necessary in any case for later technical use, and the Norwegian government would tax its emission into the atmosphere. Since October 1996 around 1Mt CO_2 has been injected annually into the sub-seabed. By the beginning of 2005 more than 7Mt CO_2 had been injected into the aquifer. By the end of the project the total should be around 20Mt CO_2. The formation has a total capacity of 1–10Gt CO_2.

The project is being observed scientifically, in part to investigate safety and permanence of storage. Initial research results indicate that a dense cap rock seals the formation at the top, preventing the leakage of CO_2. Simulation calculations covering hundreds of thousands of years suggest that the CO_2 will dissolve in the pore waters and then sink to the bottom of the formation. The probability of long-term leakage is minimal, so that the gas, according to these calculations, should not escape into the North Sea for the next 100,000 years. Even after a million years, only a millionth of the CO_2 should escape. This storage could therefore fulfil the required holding time of more than 10,000 years (Section 5.1.2), but these conclusions will have to be better documented scientifically.

Sources; IPCC, 2005; Statoil, 2005

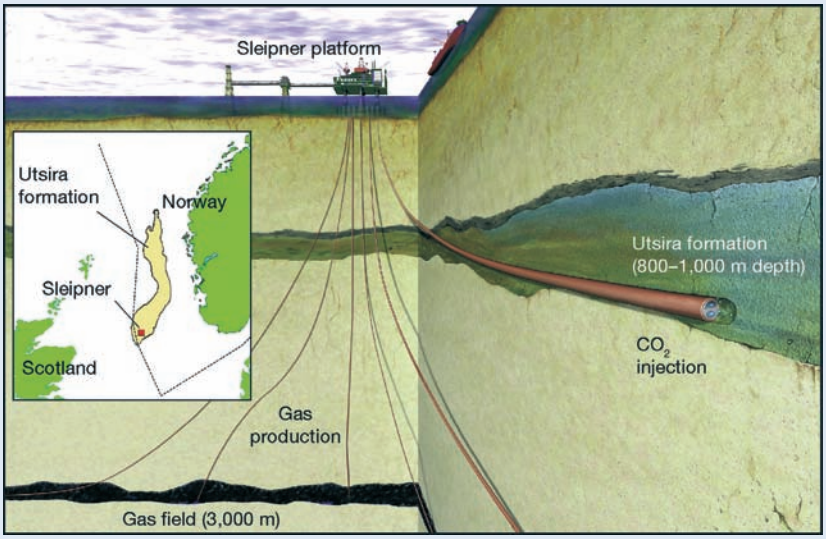


Figure 5.3-1
The Sleipner project in the North Sea, simplified representation. The gas production comes from the Sleipner East gas field. The captured CO_2 is injected into the Utsira sandstone formation. The small picture shows the position and extent of the Utsira formation in the North Sea.
Source: Statoil, 2005

than for storage on land. Even where people are in the vicinity, the probability of dangerously high CO_2 concentrations in the ocean environment is extremely low because, in contrast to the situation on land, CO_2 lakes cannot form. As a rule, such CO_2 lakes can only form and persist in depressions on land that have no or poor drainage.

As discussed in Section 5.1.2, a retention time for CO_2 of at least 10,000 years is required for long-term sustainability.

5.3.3 Regulating sub-seabed geological storage

Considering that global CO_2 emissions are rising, the option of storing CO_2 in geological formations deep below the sea floor should not be dismissed completely. However, such sub-seabed geological storage is not altogether unproblematic (Section 5.3.2). For one thing, a release of CO_2 to the atmosphere cannot be excluded entirely. This can be caused by technical faults or by accidents arising in the transport, injection and storage process. It may also be due to the selection of inappropriate geological formations. Current knowledge indicates that, under certain geological and technological preconditions, leakage rates may be acceptable (<0.01 per cent per year). There is a need for substantial further research, however, to be able to verify this with sufficient certainty. Issues in particular need of clarification include the criteria that geological formations must meet, and how any escape of the gas to seawater could be monitored and quantified.

Moreover, an all too strong political and economic focus on the sequestration option might cause neglect of far superior climate mitigation strategies, such as improving energy efficiency and switching to renewable energies. To attain the goal of sustainable energy systems, it is these superior options that particularly require political support, innovation and the employment of scarce resources (WBGU, 2004). A high renewable energy potential is available in the ocean and above the sea surface (Box 5.3-2).

WBGU therefore views sub-seabed storage of CO_2 as being, at most, a transitional option complementing other options (WBGU, 2004). Its deployment should be limited and regulated (Section 5.3.3.4).

5.3.3.1 Provisions under the international law of the sea

The 1972 London Convention and its 1996 London Protocol permit the storage of CO_2 in sub-seabed geological formations if the sequestered CO_2 originates in the course of processing the mineral resources of the seabed (Section 5.2.3; the same applies to placement of CO_2 in seawater). This is the case, for example, with the Sleipner project (Box 5.3-1).

In contrast, it has not yet been clarified unequivocally whether the 1972 London Convention or, in future, the 1996 London Protocol permits sub-seabed storage, for instance in saline aquifers, of CO_2 that was separated on land (IEA, 2005). Article III, para. 3, of the London Convention defines 'sea' as 'all marine waters'. There is some controversy as to whether this definition means that the seabed and the subsoil thereof fall within the scope of the convention. In response to a survey conducted by IMO, Germany argued in favour of construing the term 'all marine waters' to include the seabed and the subsoil thereof, as this would be in line with the history and purpose of the convention. The 1996 Protocol defines in Art. 1, para. 7, the term 'sea' more precisely, namely as 'all marine waters other than the internal waters of States, as well as the seabed and the subsoil thereof; it does not include sub-seabed repositories accessed only from land'. This definition, however, has also given rise to controversy over the depth to which the subsoil reaches. In the above-mentioned IMO survey, Germany argued in favour of construing the term as comprehensively as possible, too.

When construing the treaty wording, however, it needs to be taken into account that the issue of CO_2 sequestration, including CO_2 storage in the ocean or under the sea floor, was not on the agenda when the 1972 London Convention was negotiated, nor when its 1996 Protocol was elaborated. It is therefore not possible to draw conclusions from the wording of the treaty about the will of the participating states with respect to how to handle CO_2. The parties to the London Convention are now addressing this issue intensively (IMO, 2004), for instance at the 27th Consultative Meeting of the parties held in October 2005. In view of the numerous gaps in knowledge and the unresolved issue of whether placement of CO_2 in the seabed should be covered by the London Convention and/or the London Protocol, that meeting agreed to debate the issue in greater depth at the 28th Meeting. If the parties resolve to permit the placement in the seabed of CO_2 sequestered from separation processes on land, Annex 1 to the London Protocol may need to be amended; this would also be expedient in order to provide clarification. The pre-

Box 5.3-2

Marine renewables

In addition to their role within the climate system, the oceans offer options for active mitigation of anthropogenic climate change. On the one hand, increased utilization of renewables from the sea can substitute fossil energy carriers and therefore reduce associated CO_2 emissions. On the other hand, CO_2 storage in suitable geological formations in the seabed may offer an additional man-made sink for this greenhouse gas. The potential for marine renewables is briefly outlined below, followed by a rough comparison of the respective costs for the two options.

Potential for marine renewables

Commensurate with their proportion of the Earth's surface, the oceans receive more than 70 per cent of the solar insolation and almost 90 per cent of the wind energy (Czisch, 2005). They therefore hold the majority of the global renewables resources. However, from today's perspective only fractions of this theoretically available energy is technically and cost-effectively usable. In addition, the potential is reduced by a wide range of competing uses, particularly along densely populated coastlines. The sustainable potential is reduced further by the fact that environmental aspects have to be taken into account (WBGU, 2004). For example, any expansion of renewables must comply with the ecosystem guard rail (20–30 per cent of marine ecosystems designated as protected areas; Section 2.5). The overall area available for sustainable utilization of renewable energy is therefore reduced significantly.

- *Wind energy:* Studies on the European offshore wind energy potential (Sea Wind Europe, 2003) assume an installed capacity of 111GW and associated annual generation of 340TWh by 2015, equivalent to approximately 10 per cent of the technical potential. Siegfriedsen et al. (2003) conclude that outside the European Union approximately 4600TWh per year could be generated by offshore wind energy converters. With a total of 5000TWh per year, one-third of current global electricity demand of approx. 15,500TWh per year would be covered by offshore wind energy. In 19 of 20 countries with the largest potential outside the EU, more than 10 per cent of electricity demand could be covered by offshore wind energy converters by 2020. Of the different energy forms examined, wind energy is the most significant one in terms of potential and implementation.
- *Wave energy:* Wavenet (2003) estimates the global technological potential as 11,400TWh per year. The global sustainable generating potential of wave energy is approx. 1700TWh per year, i.e. more then 10 per cent of current global electricity demand. An annual generation figure of 9TWh is assumed for the EU by 2020. Wave energy is not expected to make a significant contribution to global electricity demand until some time in the future.
- *Tidal energy:* Strong sea currents occur near coasts through tidal and other effects. The potential for energy generation from such currents in North America, Europe, South-East Asia and Australia is estimated at 120TWh per year. The total global sustainable potential is likely to be several hundred TWh per year. In 5–10 years' time, sea current turbines could experience a similarly dynamic development as that currently seen with offshore wind energy converters.
- *Energy from osmosis:* A further energy production technique is based on the utilization of osmotic pressure between freshwater and seawater (e.g. in estuaries) using special membranes with high salt retention. This technology is currently only available at the laboratory scale. Globally, a total of 730GW could be achievable from rivers with flows of more than 500m^3 per second. The sustainable potential, taking into account ecological guard rails and shipping-sector requirements, is estimated to be around 50 per cent of the technical potential, or 2000TWh per year.

Utilization of predominantly coastal marine areas that are currently regarded as technologically accessible would offer a global total potential of approximately 9000TWh per year from wind, waves, currents and osmosis, with wind power offering by far the biggest potential and quickest implementation. However, the issue of concurrent utilization of coastal marine areas through systems for power generation from wind and waves would have to be examined in more detail, because certain wave energy systems may be difficult to combine with wind farms. In addition, high-density installation of large numbers of systems would lead to significant habitat changes, e.g. through noise emissions, increased shipping traffic and other effects such as underwater cables, so that the overall effect caused by concurrent utilization of several technologies have to be regarded as unsustainable.

Renewables vs. CO_2 sequestration

Generating costs for fossil power plants currently range between US$25 and 55 per MWh, for wind energy and small-scale hydroelectricity between US$35 and 90 per MWh (IEA, 2005). The additional costs for CO_2 sequestration relating to electricity production in fossil power plants range between 30 and 60 per cent, depending on the technology and underlying conditions. Assuming moderate future fuel price increases and further cost reductions for investments in both fossil power plants and renewables, sequestration with continued utilization of fossil energy carriers would very likely result in higher CO_2 avoidance costs than utilization of renewables in the medium and long term.

In addition, sequestration does not reduce dependence on fossil fuels and the potential for associated conflicts. Compared with CO_2 sequestration, intensive utilization of renewables is therefore regarded as the preferred option.

sent state of knowledge thus indicates that it would be necessary to take account of Art. 31, para. 1, of the Vienna Convention on the Law of Treaties, according to which a treaty shall be interpreted in good faith in accordance with the ordinary meaning to be given to the terms of the treaty in their context and in the light of its object and purpose.

5.3.3.2
UNFCCC and Kyoto Protocol

The production of the national emissions inventories in accordance with the United Nations Framework Convention on Climate Change and the Kyoto Protocol is based on the IPCC Guidelines for National Greenhouse Gas Inventories. At present, these Guidelines do not deal explicitly with the issue of sequestration. However, the IPCC Special Report on CSS (IPCC, 2005) provides for the option of applying the current framework provisions, principles and methods to sequestration activities. The Norwegian approach demonstrates how these general provisions could be applied to sequestration in practice: Norway reports the quantities of CO_2 sequestered at the offshore Sleipner facility (Box 5.3-1) and consistently factors any emissions leaked during the injection process into its national emissions (IPCC, 2005). The sequestered CO_2 is not added to the emissions inventory but is treated, in effect, as non-emitted. The Guidelines are due to be revised in 2006. It is likely that the current debate about standards for inventorizing sequestered CO_2 will flow into this process and relevant provisions will be adopted in the near future. Apart from the practical question of how to inventorize sequestered CO_2 in the national reports, a further issue to be clarified is whether, and how, sequestration projects should be integrated into the flexible mechanisms – emissions trading, the Clean Development Mechanism (CDM) and Joint Implementation (JI) (Bode and Jung, 2005; IPCC, 2005). The inclusion of sequestered CO_2 in the flexible mechanisms raises a variety of issues (Bode and Jung, 2005) which shall not be discussed in detail here. Matters become especially complicated in relation to the CDM if, for example, an Annex B country 'imports' CO_2 from developing countries which has been emitted on land and stores it in sub-seabed reservoirs which are already in use. Strictly speaking, such cases do not meet the CDM's additionality criterion, which means that in essence, no CDM emission credits can be issued. Nor does it necessarily promote technology transfer to developing countries, which is an explicit objective of the CDM. Similarly complex issues arise in relation to emissions trading and JI.

5.3.3.3
Instruments to regulate CO_2 storage in the seabed

WBGU considers that in view of the leakage risk, regulations are required for activities aimed at the storage of CO_2 in the seabed. Firstly, more rigorous minimum standards are needed, with mandatory compliance in order to minimize risks. Secondly, the use of quantity restrictions or liability-based instruments as a response to the risk of leakage would help ensure that lower-risk sustainable emissions avoidance options (e.g. increasing energy efficiency and the use of renewables) are not neglected.

Geological and technological minimum standards

The rate of CO_2 leakage over the long term must be very low and must also be readily monitored and verified. Firstly, the retention period for stored CO_2 at the chosen site must be very long – at least 10,000 years. Our current state of knowledge indicates that it is possible to meet this criterion, at least in deeper aquifers (Ploetz, 2003; IPCC, 2005). Secondly, the CO_2 storage sites must be easily monitored, i.e. it must be possible to record both the leaked and the sequestered amount of CO_2 on a reliable basis. At present, however, adequate technologies to measure CO_2 leaks are not available.

Indirect quantity restrictions

The leakage risk in particular indicates that sequestered CO_2 cannot be viewed as fully 'avoided' CO_2 emissions in international climate agreements. In the setting and implementation of emissions reductions targets, storage should therefore only be eligible in part as avoided emissions. Various approaches can be considered in this context, both at international level (UNFCCC etc.) or solely for European climate policy at first. In the following, WBGU outlines various instruments which aim to restrict by indirect means the proportion of CO_2 storage. It offers an overview of possible approaches which could play an important role in relation to sub-seabed storage as well as sequestration in general. No conclusive evaluation of the instruments can be undertaken here, firstly because no policy decision has been taken on appropriate limitation targets, and secondly because there is still a considerable need for research in many areas (Bode and Jung, 2005; IPCC, 2005).

- *Adding leakage to total emissions:* Sequestered CO_2 would only be partly recognized as avoided emissions. The percentage of CO_2 which would be considered as having been emitted 'in practice' and which would have to be designated as such in the national reports would be determined at political level. However, this percentage should not merely reflect but should significantly exceed the probable leakage, in order to take appropriate account of the impacts of leakage on the marine environment.
- *Deductions in the context of the flexible mechanisms:* Emission rights arising from sequestration

could only be traded with substantial deductions. This would mean that a certificate based on one tonne of sequestered CO_2 would give rise to an emissions entitlement of less than one tonne of CO_2. The same principle would apply to CDM credits from sequestration activities in developing countries. CDM credits could also be granted for the storage of 'imported' CO_2 from developing countries, especially as this type of cooperative project would reduce global CO_2 emissions into the atmosphere – albeit without satisfying the current CDM criteria (Section 5.3.3.2), which is why a higher deduction would be justified. The decision which deduction rate would be reasonable in individual cases would largely depend on the climate policy assessment of the leakage risk and the impacts on marine ecology. There is a considerable need for further research in this area.

- *'Traditional Action':* Countries would agree to meet a specific proportion of their emissions reduction commitments without recourse to subseabed or any other form of CO_2 sequestration. This approach would be analogous to the concept of 'domestic action'.

Liability mechanisms

When applying the above-mentioned instruments to limit CO_2 sequestration, countries implicitly make their own assessment of the scale of the leakage risk and the likely damage that leakage would cause. By contrast, liability mechanisms are an alternative or supplementary approach relying on the market mechanism. An effective liability regime for sequestered CO_2 means establishing a transparent and credible system to determine who is responsible for discharged CO_2 and who is therefore liable to pay compensation: either through ex post adding to overall emissions, ex post acquisition of emission rights, or penalty payments which are used for climate and ocean protection. As long as the operator still exists, it may be comparatively easy to enforce liability. However, the long time scale of climate protection means that the issue of liability must be clarified and safeguarded over the long term. The issues surrounding the cleanup of contaminated sites at national level have shown that it is often the state which ultimately shoulders the financial burden. This applies similarly to cases involving private operators, especially if a defunct polluting company has no legal successor or the successor lacks the resources to pay damages.

'Carbon sequestration bonds' have emerged as a market-based solution in this debate (Edenhofer et al., 2005). Here, a firm which intends to sequestrate or store CO_2 has to deposit a sum of money with a designated authority, equivalent to the amount of sequestered CO_2 multiplied by the CO_2 certificate price (Edenhofer, 2003). The company would obtain interest for the bond, equivalent to the normal market rate of interest on long-term bonds. The authority – this could be the Climate Central Bank already proposed by WBGU (WBGU, 2003) – devalues the bond according to the fraction of leaked CO_2. The balance could be used to pay for emissions prevention measures, such as the promotion of renewable energies, or even the purchase and withdrawal of emissions rights. In the case of leaks from marine disposal sites in particular, the funding of marine conservation measures from these resources would be justified. As the value of the bond falls, the interest paid also decreases. No fixed price for the devaluation of the bond is set in advance; instead, the devaluation increases over time in line with the actual amount of leaked CO_2. The idea is that the company tries to sell the right to the interest accumulating on the deposit as a 'bond' on the financial markets. This can only be achieved if potential purchasers are offered a rebate on the value of the bond which is high enough to offset the risk of devaluation by the authority. During trading, the market value would reflect not only the devaluation of the deposited amount but also the capital market's assessment of the likely leakage risk in future. The concept of 'carbon sequestration bonds' is a very interesting and innovative approach to risk assessment and liability, and merits further research.

5.4 Recommendations for action: Regulating CO_2 storage

5.4.1 Prohibiting CO_2 injection into the ocean

WBGU firmly rejects the storage of CO_2 in the ocean, i.e. in the water column and on the sea floor. The ocean is in permanent exchange with the atmosphere, with the result that this option does not mitigate the long-term consequences of CO_2 emissions for future generations. It is therefore not a sustainable option. The risk that ecosystems will suffer appreciably under an elevated CO_2 concentration in the water is a further argument against the disposal of this greenhouse gas in seawater (Section 5.2.2; IPCC, 2005; Pörtner, 2005). Moreover, the international community will scarcely be able to control CO_2 lakes on the sea floor, and the release of this CO_2 to the atmosphere over the long term cannot be excluded. WBGU therefore recommends a full and comprehensive ban on CO_2 injection into the ocean, regardless of the territorial status of waters.

The 1972 London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, in conjunction with its London Protocol (Section 5.3.3.1; the protocol has not yet entered into force) prohibit in principle the placement of CO_2 in the ocean. Both agreements, however, contain an important exception that needs to be firmly rejected in light of the above: both permit in their current wording the injection of CO_2 that arises from the production of mineral oil or natural gas, as long as the associated processing operations take place at sea. The prohibition on the injection of CO_2 arising from processing operations on land that is already implicitly in place should therefore be extended explicitly to such CO_2 that is separated in the course of seabed resource exploration and processing operations at sea. Such a prohibition could possibly be complemented by a corresponding arrangement under the Framework Convention on Climate Change; this could also serve to cover those states that do not ratify the London Protocol.

5.4.2
Limiting CO_2 storage in the seabed

The disposal of CO_2 in the seabed poses substantially less risk than its injection into the water column or on the sea floor. For that reason, and in view of the almost unavoidable rise in energy consumption especially in developing and newly industrializing countries, WBGU considers it acceptable for a transitional period to use injection into the geological sub-seabed as an option complementing more sustainable emissions reduction strategies.

WBGU accordingly recommends clarifying the issue of conformity of sub-seabed geological storage with the London Convention or London Protocol in the relevant bodies of the convention and protocol in such a way that CO_2 sequestration in sub-seabed geological formations is permissible regardless of the location of processing operations. If it should not prove possible to generate consensus on construing these legal provisions to mean that sub-seabed CO_2 disposal is permissible, then modifying or supplementing the London Protocol should be considered. WBGU also argues that such activities should only be permitted from the outset for a limited period, such as several decades.

Before the international law of the sea can be construed or supplemented in such a way, universal minimum technological standards would first need to be defined and complied with. These need to be developed specifically for marine transport, for CO_2 injection and storage, and for the characteristics and monitoring of geological disposal sites. As long as the problems currently associated with the measurement of CO_2 releases persist, WBGU advises applying exceedingly strict requirements upon geological disposal sites. WBGU takes the view that in this respect, too, the London Convention or London Protocol provides an appropriate framework for setting standards, underpinned by more comprehensive rules governing sequestration activities under the Framework Convention on Climate Change.

The IPCC Guidelines play an important role in this context. These guidelines govern the preparation of national emissions inventories. Their review is currently pending. WBGU shares the view of the IPCC Special Report (2005) that the present regulatory structure, including the flexible mechanisms, can in principle also be applied to sequestered CO_2. WBGU does not consider this expedient in all situations, but does regard it as purposeful in the case of CO_2 disposal in verified sub-seabed geological formations. WBGU recommends, however, that when sequestered CO_2 is integrated into inventories and into the flexible Kyoto mechanisms the risk of leakage be taken into account. This can be done through, for instance, deductions in emissions trading or from CDM credits, or through liability rules (Section 5.3.3.4).

5.5
Research recommendations

Risks posed by the use of geological formations for CO_2 storage

There is a need for further research on the permanence of marine CO_2 storage in deep geological formations. The associated monitoring procedures also need further development. Furthermore, research should be conducted on the potential impacts of CO_2 leakage upon marine ecosystems and organisms.

The long-term effects of storage upon atmospheric CO_2 concentrations should also be studied. An issue of particular importance in this respect is which specifications a storage site needs to meet in order to ensure stable atmospheric CO_2 concentrations at a low level over the long term. This will require an improved understanding of the carbon cycle on a millennial time scale.

Legal setting

The instruments of international law governing the permissibility of CO_2 storage in deep sub-seabed geological formations need to be studied comprehensively. Not only the London Convention with its

1996 Protocol should be taken into account. It is equally important to analyse links to other regimes in international law – notably the Framework Convention on Climate Change with its Kyoto Protocol, and the United Nations Convention on the Law of the Sea (UNCLOS).

Regulating CO_2 storage in the seabed

The manner in which geological storage of CO_2 in the seabed (and, it is worth noting, on land) may be eligible as a climate mitigation measure under the international climate protection regime needs to be clarified unequivocally in the near future. There is a need for research in the social sciences and economics on the issues surrounding the flexible mechanisms. Identifying which instruments for the limitation of sequestration are effective, efficient and enforceable in international law and policy is an issue of particular importance.

Marine renewables

Great uncertainties still attach in some instances to the renewable energy potential of marine sources such as offshore wind, wave energy, salt gradient energy or ocean thermal energy conversion. There is a considerable need for further research in order to identify the sustainable global potential. This concerns both the methods and the impacts that need to be taken into account.

Methane hydrates in the sea floor 6

Large quantities of carbon are stored in the sea floor in the form of methane hydrates, with an order of magnitude comparable to the global occurences of coal. There are risks associated with methane hydrates due to climate change as well as ocean mining. There are, however, considerable uncertainties and gaps in knowledge, so that only a preliminary evaluation of these risks is possible.

6.1 The methane hydrate reservoir

Gas hydrates – such as methane hydrates – are solids composed of water molecules that have gas molecules enclosed within their crystal lattices. Carbon dioxide, hydrogen sulphide and methane molecules have the right size to be trapped inside such a hydrate cage. Methane hydrates look like dirty ice and are flammable. They store large quantities of methane within a very small space: in the transition to the gas phase their volume increases by a factor of 170.

They are only stable under specific pressure and temperature conditions. The higher the ambient temperature, the higher the pressure has to be to prevent the methane hydrate from dissolving. The optimal conditions are typically found on the sea floor at water depths of at least around 500m, and in the Arctic starting already at lower water depth. Here, methane hydrate can form in the sediments provided sufficient quantities of methane are produced by the decomposition of organic carbon deposits. The carbon for the methane hydrate is ultimately derived from the biological production of the ocean, as dead biomass is deposited in the sediments and bacterially decomposed on the sea floor ('biogenic' methane). The formation of methane hydrates takes a very long time, so they cannot be considered as a renewable energy source: the present deposits have probably been formed over a period of several million years (Davie and Buffett, 2001). An additional, smaller hydrate source is found in leaking natural gas formations ('thermogenic' methane) from which methane bubbles rise through the sediments and under favourable conditions (i.e., in the hydrate stability zone in the cooler upper sediment layers) form hydrates with water. An example can be found in the Gulf of Mexico.

As the temperature in the sediment quickly rises with increasing depth due to the Earth's heat (at around 30°C per kilometre) but the pressure – also increasing – cannot compensate for the temperature increase, methane hydrates in marine sediments are only stable down to a certain depth in the sediments. Below the limit of this stability zone, typically several hundreds of metres thick, methane can again occur as a gas in the sediments.

Gaining evidence for the presence of methane hydrates, directly by drilling or indirectly with seismic techniques, is difficult. While the drilling that has been carried out up to now does not allow broad-area mapping of its occurrences, seismic methods can only identify the lower limit of the stability zone. On this basis, no conclusive statement can be made about the quantity of methane in sediments, because the volume of the hydrate remains unknown. These measurement problems mean that models must be used to estimate the global reservoir of methane hydrates. In the 1990s it was assumed that carbon quantities on the order of 10,000Gt C were stored in the form of methane hydrates (that equates to around twice the entire fossil energy resource: Rogner, 1997), but current estimates suggest a much lower value (500–3000Gt C: Buffett and Archer, 2004; Milkov, 2004). Klauda and Sandler (2005) presume that the largest hydrate occurrences are in the deep-sea basins rather than on the continental margins. They therefore also report a much higher estimation of 78,000Gt C, but this is based on unrealistic assumptions of the sedimentation rates of organic carbon in the deep sea. WBGU considers the estimate of 500–3000Gt C to be reliable. A comparable amount of methane is present again below the hydrates in the gaseous state (Archer, 2005). Here are some figures for comparison: at the end of 2004 the proven coal and natural-gas reserves amounted to 900Gt C and, respectively, 92Gt C (BP, 2005); the atmosphere contains 805 Gt C of carbon dioxide, of which 210 Gt C stem from anthropogenic emissions.

6.2 Methane release due to human intervention

The stability of methane hydrate deposits can be affected on the one side by global warming; on the other side, however, there are risks of an unintentional release of methane associated with the production of oil, natural gas, and possibly in the future of methane hydrate itself.

6.2.1 Response to pressure and temperature changes

Changes of pressure and temperature in the hydrate layer lead to changes in the stability zone, i.e., the depth interval in the sediment where methane hydrate is stable. Higher pressure stabilizes the methane hydrate, while warming reduces the thickness of the stability zone. Due to warming, methane hydrate will normally thaw from below (Fig. 6.2-1). Figure 6.2-1a uses a phase diagram to illustrate the stability zone in the ocean and in the underlying sediments. The red curve indicates temperature: in the ocean it decreases with increasing depth, and in the sediments it increases again due to the Earth's internal heat. The black curve shows the temperature below which methane hydrate is stable, as determined by the ambient pressure conditions. This means that methane hydrate can only exist in sediments within the depth interval where the actual temperature (red) is below the stability temperature (black). So the point where the two curves cross in the sediment represents the lower boundary of the stability zone.

If the ocean warms by 3 °C, then the red temperature curve shifts by the corresponding amount to the right (Fig. 6.2-1b). The new point of intersection of the temperature and stability-temperature curves defines the new lower boundary of the stability zone, which has shifted upward. The amount of gaseous methane below the hydrate layer has also increased by the corresponding amount.

Figure 6.2-1c assumes that the ocean rapidly warmed by 8 °C, so that the temperature curve is completely to the right of the stability-temperature curve, and therefore hydrate is no longer stable at any depth. Whereas with a 3 °C ocean-temperature increase the total sediment depth down to the base of the stability zone first has to warm before the methane hydrate begins to dissolve at all, in the example with an 8 °C increase the destabilization of the hydrate would begin at the sea floor, i.e., before the total sediment layer has warmed. In the course of the temperature rise the methane hydrates would dissolve completely from above.

6.2.2 Effects of climate change on methane hydrates

Global warming leads to temperature changes in the ocean as well as to changes in sea level, and therefore to pressure changes on the sea floor. Figure 6.2-2 provides an overview of the effects this can have on methane hydrate deposits.

In pessimistic IPCC scenarios the average sea-surface temperature increases by the end of this century to 5 °C above the pre-industrial level. Regionally, for example in the Arctic, this value could be as great as 10 °C. The high latitudes are of global importance

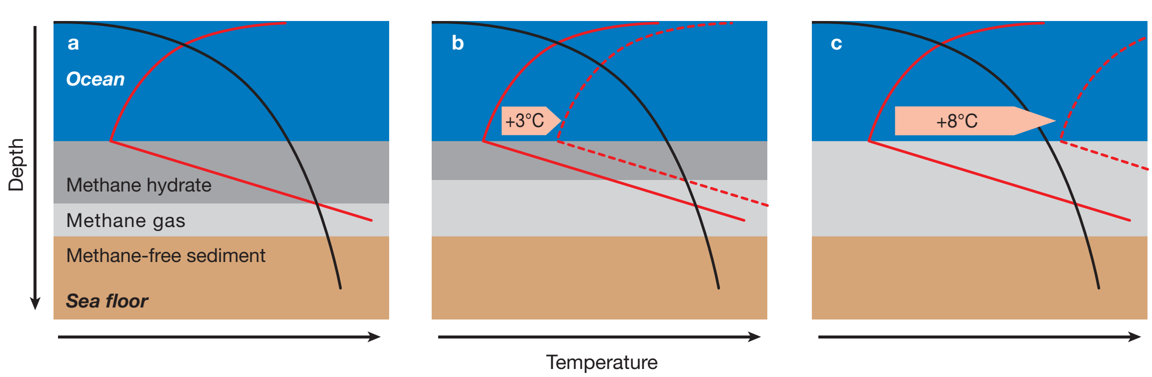


Figure 6.2-1
Changes in the methane hydrate layer due to warming. The black curve describes the stability temperature dependent on depth. The red curve shows the actual temperature; red dashed lines show schematic temperature profiles after a warming of 3 °C (stability zone of hydrates becomes thinner from the bottom) and 8 °C (stability zone completely disappears), respectively. Source: WBGU

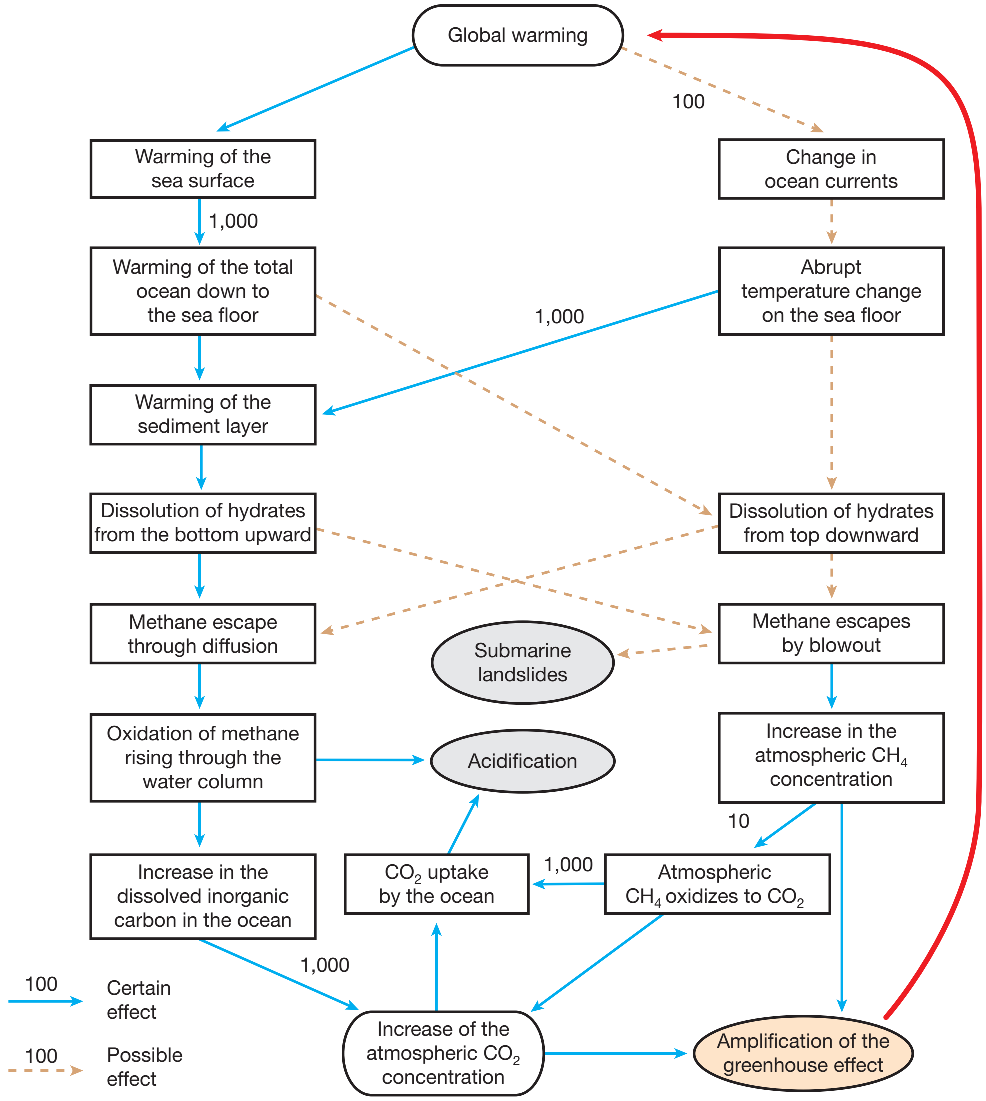


Figure 6.2-2
Causes and effects of methane hydrate destabilization. The mechanisms are discussed in the text. Numbers above the arrows indicate the respective time scale of the process in years (no number given = immediate effect).
Source: WBGU

because it is here that the cold-water masses originate that fill the deep sea worldwide. Because of the stable temperature layering and the slow mixing of the ocean, the warming, as a rule, will only penetrate to the sea floor very slowly, over the course of several centuries. Similar time frames are necessary in order to warm the sediment layers down to several hundreds of metres. Only under very special local conditions – with hydrate occurrences at shallow sea depths and in well-mixed marine regions – could hydrates become unstable in the short term (within this century) due to warming. An escape of hydrates on a large scale (that is, enough to have a noticeable impact on climate) is not an acute but a long-term danger. Over a period of centuries a reinforcing feedback loop with global warming could occur, which over time could become increasingly difficult to check.

Relatively rapid and intense local temperature changes could occur when marine currents are altered, a danger that is commonly discussed with respect to the northern Atlantic (Section 2.1.3). The development of temperature at the sea floor seems to depend strongly on how the circulation changes (Mignot et al., submitted) and is therefore difficult to predict. Simulations suggest, however, that after a breakdown of the deep-water formation in the Norwegian Sea the bottom temperature in some regions of the North Atlantic could quickly rise by over 7 °C. Changes at this order of magnitude could then also destabilize hydrate reservoirs.

An additional factor is the rising sea level, which, by increasing the pressure on the sea floor, could in principle stabilize the hydrate deposits. Here only the volume of water released by melting land ice masses is relevant because thermal expansion would not increase the pressure. The effect, however, is very small: in water depths of 400 m a pressure increase of 0.04 MPa (corresponding to a sea-level increase of 4 m) results in an increase of the destabilization temperature of less than 0.1 °C. The long-term sea-level rise can therefore not compensate for the effect of the long-term warming on hydrate stability. The same is true for short-term relative changes in sea level resulting from circulation changes (Levermann et al., 2005), the results of which cannot compensate for the abrupt temperature changes they also cause.

If the methane hydrate stability zone is reduced, then methane gas forms below the hydrate layer. This gas can either penetrate through the hydrate layer and escape out of the sea floor through small channels or permeable sediment layers, or it can blast through the hydrate layer if sufficient quantities of gas collect below a continuously thinning layer. In such a blowout large amounts of methane gas are abruptly released. Because the shattered blocks of methane hydrate released are less dense than water, they rise to the surface and dissolve there.

The quantity of methane gas that would escape from the hydrate layers by one of these mechanisms in the future can presently only be roughly estimated, because the stability and permeability of sediment layers are dependent on highly variable local conditions.

6.2.3 Mining of methane hydrates

Methane hydrates represent a source of fossil fuel and can therefore be of interest for commercial exploitation. The economic feasibility of their recovery depends greatly on the available methane concentration in the hydrate. The few examples of practical experience obtained in exploiting methane from hydrate deposits are from the Messoyakha gas field (Siberia) and the Mallik (Alaska) research project. The Russian Messoyakha gas field is an occurrence below permafrost that was discovered as early as the 1960s. Not only were the mining costs here extremely high, but it has also come into question whether the methane recovered here in the 1970s really was, as claimed, retrieved from hydrate deposits (EIA, 1998; Schindler and Zittel, 2000a). Mallik 2002 is a drilling project on the Arctic coast of Canada, where the methane concentration of the hydrate is rated similar to that found in Japanese coastal waters. The project included gas hydrate production tests and is part of an international research consortium in which states (incl. USA, Japan, India and Germany) and companies are participating.

In principle, the mining of methane hydrates on the high seas would be possible. It is considered technically feasible to drill into the sea floor in water depths up to four kilometres. The technical and especially the economic practicability of potential recovery mining methods is a subject of research in which Japan and the USA are playing particularly important roles. The Japanese programme for methane hydrate mining (National Methane Hydrate Exploitation Program, MH21), among other aspects of methane hydrate research, is expressly pursuing the ambitious goal of beginning production tests in 2007 and is aiming to have the technology for commercial large-scale production by 2012 (MH21, 2005). Financing for the US American methane hydrate research programme (Methane Hydrate Research and Development Act of 2000) was extended through 2010 by the Energy Policy Act of 2005. Commercial mining of methane hydrate in US American waters is deemed possible by 2015 and large-scale mining by 2020 (DOE-NETL, 2005; Ray, 2005).

These expectations are compatible with the estimation that methane hydrate mining will be economically feasible in some regions within the next 5–10 years, while it would take 30–50 years before worldwide massive mining is possible (Methane Hydrate Advisory Committee, 2002; Collett, 2005). Methane hydrate exploitation in permafrost areas on land could reach industrial proportions more quickly than the exploitation from the sea (Johnson, 2004). That is because progress in the identification and evaluation of occurrences feasible for exploitation on land is ahead of that for occurrences beneath the sea. In addition, there has already been extensive experience gained in recovery and production technology on land (Mallik research drilling, Messoyakha gas field). The more favourable recovery conditions compared to the sea also make it likely that mining will first be carried out on land. In combination with economies of scale and learning effects, there could therefore be cost advantages. Overall, this means that there is an initial advantage for methane hydrate exploitation on land over that at sea. The predicted technological feasibility as well as the economic and energy-strategic potential of this kind of energy production, however, is critically questioned and considered to be clearly overestimated (Schindler and Zittel, 2000b).

Targeted research into the production of marine methane hydrate has been limited so far to a few pilot studies. They probably will not go beyond the stage of feasibility studies during this decade.

6.3 Possible results of methane release

The consequences of a release of methane gas from hydrates depend on the mechanism – 'diffusion' or 'blowout' – as well as the time scale of the release.

When methane gas diffuses through the hydrate layer and slowly escapes in small bubbles from the sea floor, a large portion of it will probably be dissolved in the water column as it rises. A new study shows, however, that methane bubbles could also possibly rise through the upper water layers and escape into the atmosphere (Sauter et al., 2006). Dissolved methane in the ocean has a lifetime of about 50 years before it oxidizes to H_2O and CO_2. A large portion of the released methane would therefore be released to the atmosphere before it oxidizes. Firstly, the remaining oxidized portion would increase the concentration of dissolved inorganic carbon in the ocean, which contributes to further acidification (Section 4.1). Secondly, an equivalent decrease in oxygen concentration would occur. For comparison: in order to exhaust all of the $2 \cdot 10^{17}$ mol of oxygen contained in the ocean, it would have to react with 1000 Gt of methane (Archer, 2005). Thirdly, in the long term, a new carbon-equilibrium state would be established between the atmosphere and ocean, over the course of about 1000 years, and about one-fifth of the carbon incorporated in the ocean released into the atmosphere. The concentration of CO_2 in the atmosphere would thereby increase, strengthening the greenhouse effect. Hence, over the long term, this effect would come about in any case: the result is the same whether methane escapes directly into the atmosphere and oxidizes there to CO_2, four-fifths of which is gradually taken up by the ocean, or if it is first released in the ocean, oxidized there, and one-fifth is given off to the atmosphere.

When large quantities of methane are suddenly released, most of it will reach the water surface and abruptly increase the methane concentration in the atmosphere. Because methane is a considerably more effective greenhouse gas than CO_2 (around 25 times stronger per molecule) due to its much lower concentration and therefore less saturated absorption bands, the effect of comparatively low amounts of methane is significant. But atmospheric methane quickly oxidizes (with an average residence time of eight years), to CO_2, which accumulates in the atmosphere due to its long life expectancy, so that in the long term the escaped methane after its oxidation to CO_2 has an even greater impact on climate than before.

Figure 6.3-1 shows how anthropogenic CO_2 emissions can lead to methane emissions from hydrate deposits over the coming millennia. A total emission of 1000 Gt CO_2 is assumed. Figure 6.3-1a reveals how strongly this could cause the atmospheric methane concentration to increase, whereby the uncertainty of the time scale of the release is taken into account with three different assumptions.

Figure 6.3-1b illustrates the climatic consequences of the methane emissions for the 1000 Gt of CO_2 scenario for the case of a methane release within 1000

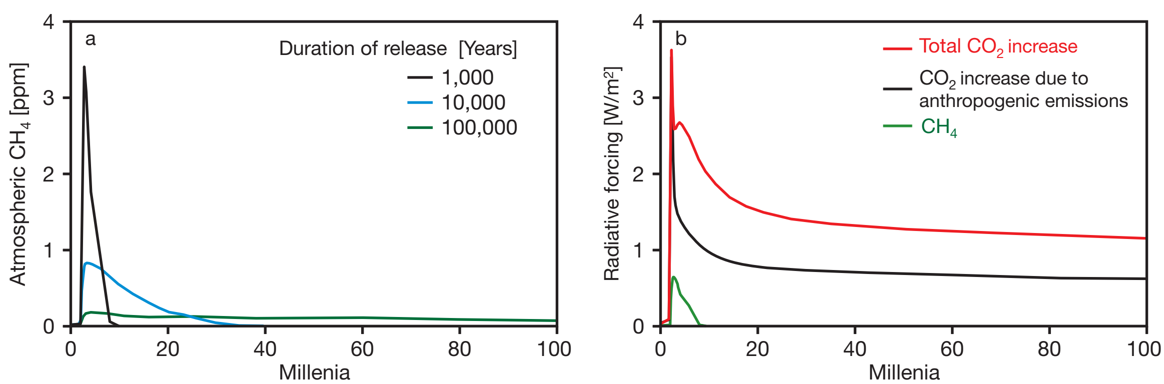


Figure 6.3-1
(a) Atmospheric methane concentration for a scenario with a total quantity of 1000 Gt of anthropogenic CO_2 emissions. The curves describe the resulting methane release over different time frames (1, 10, and 100 thousand years). (b) Climate-impacting radiative forcing for the case of the shortest release period of 1000 years. This is a combination of the forcing due to methane itself (green; it gradually oxidizes to CO_2 and thus disappears), that due to anthropospheric CO_2 emissions (black), and CO_2 from the oxidation of methane. The last two together yield the radiative forcing due to the total increase of CO_2 (red).
Source: Archer und Buffet, 2005

years. The results are caused both directly through the increase in atmospheric methane concentration (green), as well as on a longer time scale by the increase of the CO_2 concentration (red). Although the direct methane effect is lower than that of the original anthropogenic CO_2 emission, the subsequent increase in CO_2 concentration through oxidation of the methane leads, over the long term, to a near doubling of the greenhouse effect.

Methane eruptions can also present other dangers. They can destabilize continental slopes and trigger large submarine landslides, which can then possibly result in the break-up of additional hydrates. Evidence of such slides can be found on the sea floor. For example, in the Storegga landslide off the coast of Norway around 8000 years ago, an average of 250m of the continental slope with a width of 100km were transported downslope (Archer, 2005). This event triggered a tsunami that was at least 25m high off the Shetland Islands and at least 5m high along the British coast (Smith et al., 2004). The amount of methane released by this landslide is estimated at 0.8Gt C (Archer, 2005). When this amount of methane directly enters the atmosphere, it can alter the radiative forcing by as much as 0.2W per m^2 (for comparison, today's radiative forcing due to anthropogenic greenhouse gases is 2.7W per m^2). This example illustrates that an abrupt release of methane, even in the case of a large catastrophic slide of the continental slope, would only have a relatively minor impact on climate.

6.4
Recommendations for action: Preventing methane release

Through the warming of seawater, anthropogenic climate change can lead to a destabilization of methane hydrate deposits on the sea floor. According to the present state of knowledge, however, the danger of a sudden release of large, climate-influencing quantities within this century is very small. Of much greater importance is the probability of a continuous methane release over many centuries to millennia due to the slow intrusion of global warming into the deeper ocean layers and sediments. The consequences of human actions persist in this respect not just over centuries, but could influence the Earth's climate over tens of thousands of years.

Limiting global warming follows once more here as a recommendation for action, because methane release from hydrates could further amplify climate change in the long term. This feedback effect presents the danger that humankind could lose control of the greenhouse-gas concentration in the atmosphere, as the outgassing of methane from the sea floor cannot be controlled or limited.

There is already a need today for institutional action with regard to marine methane hydrate deposits. This is with respect to, for one, the targeted mining of marine methane hydrates, and for another to the unintentional release of methane that could occur during sea-floor mining.

Theoretically, efforts to recover methane from hydrates could unintentionally trigger their release into the environment, in the worst case as a sudden eruption. The risks of this have not yet been sufficiently investigated (Archer, 2005). A leak of methane into the environment during mining would unnecessarily amplify global warming. In the worst case even a slope slide could be caused that could trigger a tsunami.

The risks associated with mining are very variable depending on the geological conditions. The risks of methane mining therefore have to be carefully reviewed for each individual case. An environmental impact assessment along with monitoring according to universal standards is necessary for every case.
The International Seabed Authority, an institution of the international United Nations Convention on the Law of the Sea (UNCLOS), is responsible for methane hydrate deposits as well as for other resources on the sea floor outside the exclusive economic zone. The Authority grants mining licenses and monitors mining operations. Its regulations adopted in 2000 for the exploration of deep-sea mineral resources contain various environmental aspects. This is a starting point for agreement on concrete standards for mining marine methane hydrate on the high seas. In the opinion of WBGU it is furthermore necessary to improve and expand the monitoring system. It is, however, important to note here that so far 'only' about 150 countries have ratified UNCLOS, and of those only about 120 countries have ratified the rules governing seabed resources (those who have not signed include, for example, Iran and the USA). A framework within which more countries can be persuaded to accede to the agreements for maintaining universal standards in hydrate mining still needs to be worked out. Also needed are agreements binding under international law for the mining of methane hydrates in marine regions that lie within the territorial sovereign rights of coastal nations (Box 2.6-1). This is necessary considering that both the above-mentioned Japanese pilot project and American plans target future commercial methane production from hydrate deposits in national coastal waters.

The danger of methane hydrate release also exists in principle in other sea-floor mining activities. If methane were to be destabilized and unintentionally released in the mining of resources, these emissions would hardly be measurable, and therefore not accounted for in the emissions inventory of a country, or only insufficiently so. The applicable IPCC guidelines of 1996 for national emissions inventories do not include methane that is unintentionally emitted at sea. WBGU therefore recommends for the upcoming reworking of the guidelines in 2006 that this omission be corrected despite the difficulties in measurement. But at the very least a reporting obligation should be introduced for such releases of methane.

6.5 Research recommendations

Because estimates of the risks of methane release are still hampered by large uncertainties and gaps in knowledge, there is a significant need for research. To begin with, the methane occurrences need to be more extensively mapped and quantities estimated. The primary focus here should not be on the potential workable deposits, but on occurrences that could possibly become destabilized by climate change, and on the danger of slope slides. Furthermore, modelling studies should be employed to investigate which regions of the ocean show the greatest risk for hydrates to become destabilized through global warming.

While research on the long-term stability of marine methane hydrates and climate protection implications should continue to be strengthened, WBGU sees no need for government subsidies for applied research for the mining of marine methane hydrates. Public funding of such projects does not seem purposeful because mining poses considerable risks and methane hydrates do not represent a sustainable energy source.

There would, however, be a need for targeted natural science research if appropriate standards for the mining of marine methane hydrates need to be defined. Natural science investigations should be supplemented by social science and legal studies of the prospects for worldwide implementation of such standards.

Climate mitigation for marine conservation

The future of the marine environment will depend crucially upon whether human-induced disruption of the climate system can be limited to a tolerable level. It follows in WBGU's view that global anthropogenic greenhouse gas emissions will need to be approximately halved by 2050 from 1990. Because of the geophysical time lags, the climate protection policies adopted in the next few decades will determine the state of the oceans for millennia to come. Adaptation measures can only succeed if the present acceleration of sea-level rise and the increasing acidification of the oceans are halted.

WBGU has already formulated a 'climate guard rail' in earlier reports as a contribution to making a sustainable development pathway operable: to prevent dangerous climatic changes, the mean global rise in near-surface air temperature must be limited to a maximum of 2°C relative to the pre-industrial value and the rate of temperature change must be limited to a maximum of 0.2°C per decade. The present report shows that marine conservation is a further reason why it is essential to obey this guard rail.

Bolstering the resilience of marine ecosystems

Fish stocks and coral reefs will only retain their productivity and diversity if sustainable marine resource management is ensured worldwide. The mounting direct and indirect pressures generated by anthropogenic greenhouse gas emissions are making adoption of an 'ecosystem approach' for the conservation and use of the marine environment ever more important. To that end, the establishment of marine protected areas, an approach already agreed by the international community, must be pushed forward energetically, and the regulatory gap for the high seas must be closed by adopting a corresponding agreement within the framework of the United Nations Convention on the Law of the Sea (UNCLOS).

To conserve marine ecosystems and strengthen their resilience, WBGU proposes the following guard rail: at least 20–30 per cent of the area of marine ecosystems should be designated for inclusion in an ecologically representative and effectively managed system of protected areas.

Limiting sea-level rise and reorienting coastal zone management strategies

The strategies hitherto adopted to protect and utilize coastal areas are no longer adequate to cope with climate-driven sea-level rise and the mounting destructive force of hurricanes. Novel combinations of measures (portfolio strategies) are called for, whereby the options of protection, managed retreat and accommodation need to be weighed against each other. In particular, coastal protection and nature conservation concerns must be better linked, and the people affected by adaptation or resettlement measures must be involved in the planning and implementation of such measures. To this end, WBGU recommends creating integrative institutions that combine all key competencies.

To prevent severe damage and losses from occurring, and to avoid overstretching the adaptive capacity of coastal ecosystems and infrastructure, WBGU proposes the following guard rail for sea-level rise: absolute sea-level rise should not exceed 1 m in the long term, and the rate of rise should remain below 5 cm per decade at all times.

Adopting innovative instruments of international law for refugees from sea-level rise

At present no nation has any obligation under international law to receive migrants whose homeland has been lost due to climate-induced flooding. In the long term, however, the international community will not be able to ignore the issue of 'sea-level refugees' and will therefore need to develop appropriate instruments for the secure reception of affected people in suitable areas, ideally in areas that correspond to their preferences. It would be expedient to develop a fair burden-sharing system, under which states make a binding commitment to assume responsibility for these people in line with their greenhouse gas emissions. To inform the policymaking process, studies in the fields of law and social sciences should be undertaken.

Halting ocean acidification in time

The oceans have absorbed about one-third of all anthropogenic CO_2 emissions to date, which has already caused a significant acidification (decrease in pH) of seawater. These emissions thus influence the marine environment directly – in addition to the route via climate change. Unabated continuation of this trend will lead to a level of ocean acidification that is without precedent in the past several million years and will be irreversible for millennia. The effects upon marine ecosystems cannot be forecast exactly but profound changes to the food web are conceivable, as calcification of marine organisms may be impeded or in some cases even prevented. WBGU recommends fostering internationally coordinated research and monitoring programmes on this issue. Furthermore, the negotiations on future commitments under the United Nations Framework Convention on Climate Change need to take into account the special role of CO_2 compared to other greenhouse gases. Besides stabilizing the overall package of greenhouse gases, it will be important to also seek explicitly to stabilize CO_2 concentrations.

To protect the oceans against acidification, WBGU proposes the following guard rail: in order to prevent disruption to calcification of marine organisms and the resultant risk of fundamentally altering marine food webs, the pH of ocean surface waters should not drop more than 0.2 units below the pre-industrial level in any larger ocean region (i.e. also in the global mean).

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