RECENT INFORMATION ON THE IMPACTS OF CLIMATE CHANGE

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Приведены последние научные данные о некоторых воздействиях изменений климата. В частности, рассмотрены такие вопросы, как глобальный подъем средней температуры и его усиленное воздействие в Арктике, подъем уровня моря, подкисление океана.

Introduction

Anthropogenic climate change is the climate change caused by human interference with the climate system. Article 2 of the UN Framework Convention on Climate Change (UNFCCC) states that dangerous anthropogenic interference with the climate system must be prevented, by stabilising the concentration of greenhouse gases in the atmosphere. The stabilisation level and the time-frame required to achieve it must fulfill the following conditions:

— ecosystems must be able to adapt naturally;
— food production may not be threatened;
— the economy must be able to develop in a sustainable manner.

In this context, a discussion is going on about the choice of adequate temperature targets associated with stabilisation levels of greenhouse gas concentrations. In 1996, the EU opted for the 2 °C target. This choice was re-confirmed at the council meeting of EU environment ministers in December 2004.

The choice of a temperature target in the context of Article 2 requires scientific information on the consequences and risks of a variety of options to achieve this target as well as a consideration and a balancing of the interests involved. In this paper, recent scientific information on some effects of climate change that is important to such a consideration is discussed. The related costs (damage, costs of mitigation or adaptation measures) will not be dealt with.

The following issues are presented:

— *global mean temperature rise, and its amplified effect in the Arctic.* Through this amplified Arctic temperature rise not just impacts in the Arctic itself will occur, but also global effects, due to the greater contribution to sea level rise and the possible release of methane caused by melting permafrost;

— *sea level rise,* in this century and thereafter. Scientific uncertainties about the relationship between increasing temperature and the magnitude of future sea level rise mean that this is still difficult to quantify. The uncertainty is increased due to the possible larger contributions from ice sheets melting;

— *ocean acidification.* The uptake of anthropogenic CO_2 by the oceans changes the seawater chemistry and will significantly impact calcifying organisms and the marine food chain. Ultimately, the CO_2 uptake capacity of the oceans could decrease, resulting in accelerated global warming.

1. Changes in global mean and arctic temperatures

Past global temperatures
Information about past temperatures can be obtained by measurements and by reconstructions (proxies). This information can be checked versus model simulations.

For quite some time there is a debate going on about the so-called hockeystick graph: the earth surface temperature during the past thousand years. The main controversy regards the first part of the graph and not so much the temperature increase during the last decades. In this context, we don't aim to deliver a comprehensive discussion; we just touch upon the subject, presenting some recent information.

Various evidence
Wentz and Vinnikov compared observations with simulations from 20 different climate models [1]. They found that over a 25-year satellite record, the surface and the midtropospheric each warmed roughly 0.15 °C per decade averaged over the globe, give or take 0.05 °C or so per decade.

A report, recently released by the US Climate Change Programme contains the following conclusion: Globally, as well as in the tropics, the temperature of the air near the Earth's surface has increased since 1958, with a greater rate of increase since 1979. Temperature increased at a rate of about 0.12 °C per decade since 1958, and about 0.16 °C per decade since 1979 [2].

And finally, a recent publication [3] reports about the findings of the US National Research Council (NRC): the last decades of the 20^{th} century were most likely warmer than any comparable period in the past 1000 years; a confirmation of the pattern: warm (10^{th} and 11^{th} century) — cool — much warmer.

Example of a proxy
Oerlemans [4] related changes in glacier length to changes in temperature. Firstly, he observed that a mean glacier retreat started around 1800 and then accelerated gradually. From 1900 to 1980, 142 of the recorded 144 glaciers retreated. Glacier retreat on the century time scale seems to be fairly uniform around the globe. There are strong indications that glacier fluctuations on a continental scale are, over decades to centuries, primarily driven by temperature. This enables the reconstruction of temperatures from these fluctuations, fully independent of other sources (proxy or instrumental). Oerlemans found that most regions show a temperature increase from 1860 onwards. In the first half of the 20^{th} century the temperature rise is notably similar for all regions in the world: about 0.5 K in 40 years. After 1945, the global mean temperature drops slightly up to 1970, when it starts to rise again. This result provides additional evidence about the magnitude of the current global warming, the time that this warming started, and the notion that in the lower troposphere the warming appears to be independent of elevation.

In conclusion, it can be stated that over de last 3–4 decades we can see an increase of 0.12…0.16 °C per decade in the average surface temperature of the Earth. There is general agreement that part of this warming is caused by building up of heat-trapping gases, mainly emitted by burning coal and oil.

The future

The magnitude and impact of future global warming depends on the sensitivity of the climate system to changes in greenhouse gas concentrations. The climate's sensitivity is expressed in terms of the global mean increase of (surface) temperature (in °Celsius) resulting from a doubling of CO_2 (equivalent) concentration in the atmosphere compared to the pre-industrial level, i. e. approximately 550 ppmv. The actual climate sensitivity value is uncertain. The most significant reasons for this uncertainty have to do with our current poor understanding of the effect of increasing greenhouse gas concentrations on cloud formation. An increase in the concentration of greenhouse gases also leads to more water vapour in the atmosphere, which itself also has a greenhouse effect. This effect, though, depends strongly on the level of water vapour increase, and whether this increase occurs in the clouds or outside them. Furthermore, the effect of clouds on the climate can change due to changes in the geographic distribution; the effect depends on the type of cloud cover, the amount of water that the clouds contain, the mean size of droplets and ice crystals, etc. Lastly, it is not really possible to use historical temperature observations to give a statistical indication of the range of the climate's sensitivity, partly because of the 'global dimming' effect, the tempering influence of aerosols on past temperatures [5].

The Intergovernmental Panel on Climate Change (IPCC) has adopted a probability range for the climate's sensitivity between 1.5 and 4.5, with 2.5 as the median estimate. Based on this median estimate, a stabilisation of greenhouse gas concentrations at 550 ppmv would lead to an ultimate temperature increase of nearly 2.5 °C. If we are to stay under 2 °C, the concentration must be stabilised at a level below 550 ppmv. Since the last IPCC Report [6], a number of new studies have appeared that have used a variety of approaches to construct probability density functions for the climate sensitivity value (see Fig. 1). The most recent insights give ranges (probability range per cent) of 1.5. . . 6.2 °C [7] and 1.5. . . 4.5 °C [8].

Arctic temperature rise and its impacts

During the past few decades the average temperature in the Arctic has risen nearly twice as fast as in the rest of the world. There are certainly regional variations caused by wind patterns and ocean waves, which means that some areas have warmed up more than others, while a few

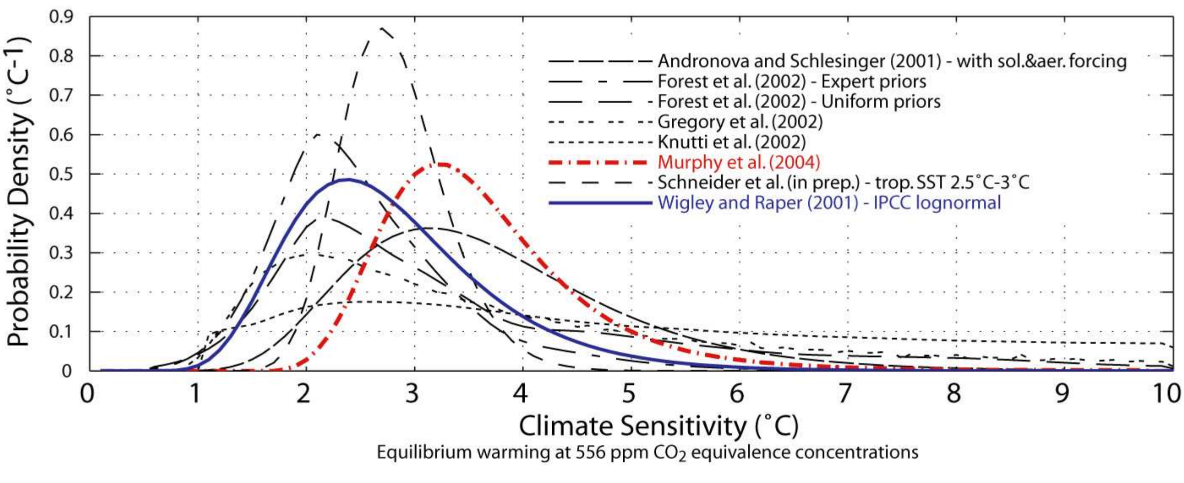

Fig. 1. Probability density functions for climate sensitivity (Source: Hare and Meinshausen, 2004).

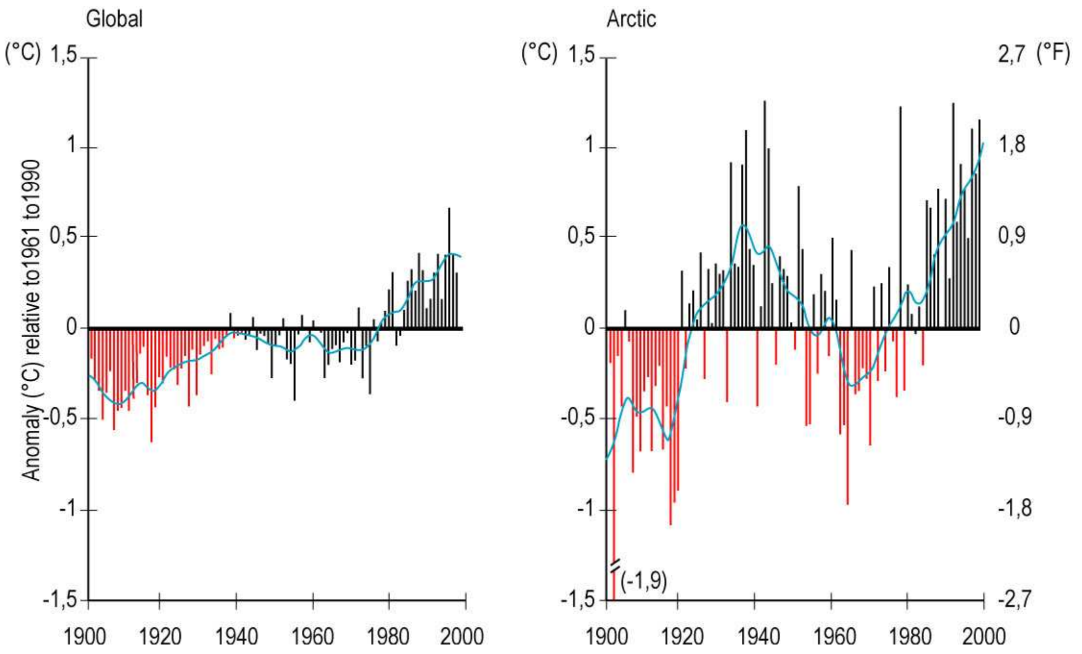

Fig. 2. Anomalies of observed global average land surface air temperature [6] and Arctic near surface air temperature [9], 1900 to present, relative to the average for 1961–1990.

areas show a slight cooling. However, the Arctic as a whole displays a clear trend of amplified warming over the global mean (see Fig. 2).

A number of mechanisms are responsible for this (see Box). The Arctic Climate Assessment [9] reports on the consequences for humans and the environment (ACIA being a four-year study, completed in 2004 and conducted by more than 250 scientists and members of indigenous populations).

Warming during the past few decades was found to be accompanied by melting glaciers and sea ice, as well as higher permafrost temperatures. There are indications that a large area, stretching for a million square kilometres across the permafrost of western Siberia, is turning into a mass of shallow lakes as the ground melts (New Scientist.com news service, 11 August 2005). Melting permafrost is a major source of feedback that could accelerate climate change by releasing either CH_4 into the atmosphere (in wet conditions) or CO_2 (from dry soils). Larry Smith of the University of California, Los Angeles, estimates the west Siberian bog alone to contain some 70 billion tonnes of methane, a quarter of all the methane stored on land surfaces worldwide.

Associated effects of melting glaciers and sea ice are loss of albedo, sea level rise and a decrease in salinity of the northern seas as a result of melting ice, and an increase in the inflow of river water from melting glaciers. The last-mentioned two processes may lead to a weakening of the Thermohaline Circulation.

Some of the consequences for the Arctic itself involve a retreat of sea ice (with adverse consequences for many mammal species), changed shipping routes (a beneficial effect), shifting zones of vegetation, disintegration of the permafrost, and economic and cultural consequences for the indigenous people. Disintegration of the permafrost leads to damage to buildings, roads, oil/gas plants and pipelines, and could result in serious environmental problems.

A global average warming of 2 °C (as is considered by the EU) corresponds to an increase of 4. . . 8 °C in the Arctic. Calculations with various computer models predict that this sort of warming will result in almost the entire disappearance of Arctic sea ice in the summer towards the end of the present century [10]. This will threaten the survival of the polar bear, ice-dependent seals, walruses and a number of seabirds. The tundra forms a breeding area for more than 20 million geese and wading birds. Many of these species will experience the adverse effects on tundra ecosystems, which are predicted to occur when the warming climbs to 2 °C.

According to the Hadley Centre [11], the quantity of Arctic ice was constant until the 1960s. From 1970 it has declined by 7.5 %, which corresponds to about one million square kilometres. This cannot be explained solely in terms of natural causes. If human activities are included in the Hadley Centre model, the model simulations agree with the observations. Human interference can thus be concluded to cause the Arctic ice to melt.

2. Sea level rise

One of the important impacts of global climate change is sea level rise. Sea level movement is a natural phenomenon, but this can be reinforced by anthropogenic climate change.

Natural changes in sea level can be very large. For example, during the last glacial era, which ended about 10 000 years ago, the ocean was 120 metres lower than it is now [12]. 130 000 years ago, (the previous inter glacial period), the mean global sea level was 4 to 6 m higher than today.

Global mean sea level rises can occur due to an increase in the volume of water in the oceans. During the 20th and 21st centuries this is likely to be the result of thermal expansion of sea water and the melting of glaciers and changes in the mass of the Antarctic and Greenland ice sheets [13]. The process of thermal expansion is characterised by a long delay after a temperature increase, meaning that it is necessary to look several centuries ahead (see Fig. 3). Church suggests that the most important contribution to 20th and 21th century sea level rise is likely to be thermal expension of the oceans. However, Thomas et. al. [14] state that half the

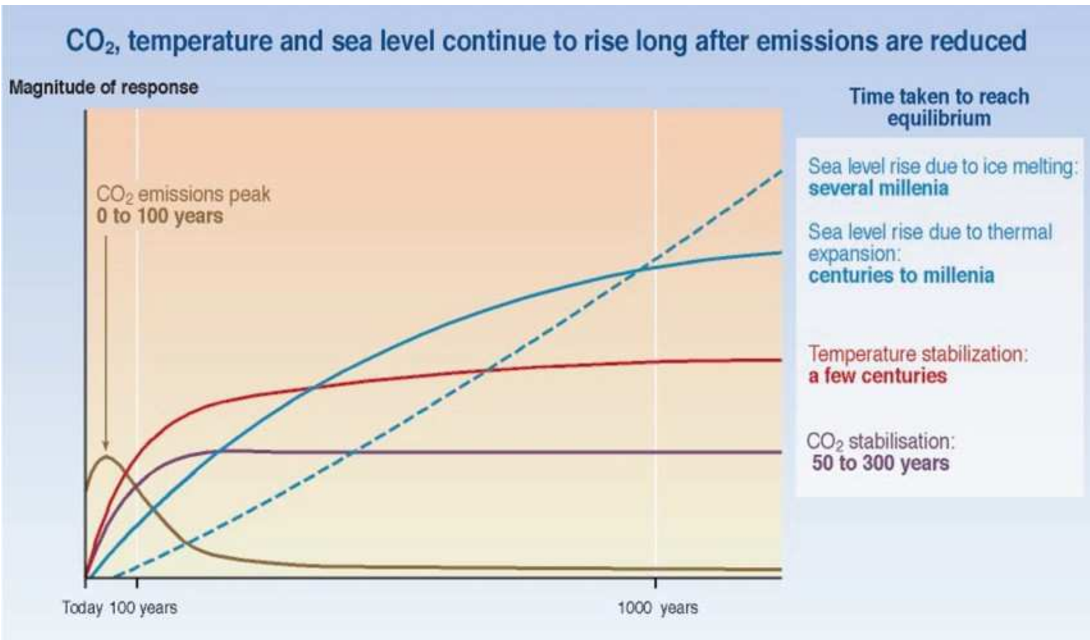

Fig. 3. Time lags in the climate system.

recent sea level rise is due to the melting of ice from Greenland, West Antarctica's Amundsen Sea and mountain glaciers.

The sea level change *at a given locality*, also termed the relative sea level change, depends on yet more factors:

— regional variations, including those caused by non-uniform patterns of temperature and salinity changes in the ocean. These can cause deviations (up to 100 %) from the world mean sea level rise [15];

— vertical movements of the land surface caused, for example, by tectonics, and land subsidence due to large-scale water extraction or compaction of peatlands.

The relative sea level rise is thus the sum of the global mean sea level rise, the regional component and the local, vertical component.

Global mean sea level rise during the 20th century was 10–20 cm [13]. This figure is derived from measurements that have been corrected for vertical land movements. Rapley estimates the current rate of sea level rise at ca. 1.8 mm/year [12].

With regard to the *future*, one must take account of the response to future emissions as well as the continuing response to past ones – the delayed effect of past greenhouse emissions (see Fig. 3). This last factor, which is largely governed by the thermal expansion, will continue to play a part for many centuries to come, due to the long-term process by which surface heat mixes with the deeper layers of the ocean.

Based on a number of emission scenarios, the Intergovernmental Panel on Climate Change expected in its 2001 report [6] the global mean sea level to rise in 2100 by 9…88 cm. This broad range can be ascribed to scientific uncertainties and different assumptions about population growth and economic development, which also translate into the temperature projection range. Furthermore, a part is also played by uncertainties about the growth of the ice sheets due to precipitation and calving, and the degree to which the temperature increase is distributed over the ocean. The increase can principally be ascribed to thermal expansion. The range of 9…88 cm does not incorporate the major uncertainties attached to possible large changes in the West Antarctic Ice Sheet (WAIS) and the Greenland Ice Sheet, see next para.

Model calculations indicate a future global mean sea level rise that is practically independent of future emissions until ca. 2050 [16]. However, after 2050, future emissions assume increasing importance in managing the sea level rise over a period of centuries. A global mean sea level rise is thus unavoidable during the 21st century and thereafter. But we can influence the (rate of) sea level rise in the 22nd century and thereafter by cutting greenhouse gas emissions in the current century.

Stabilisation of the concentration of greenhouse gases in the atmosphere, via certain emission pathways (in association with certain mitigation measures), will limit the temperature increase and therefore also the thermal expansion of sea water that leads to sea level rise. Nevertheless, the delayed effect of past emissions means that adaptive measures will have to be taken in any case.

Melting of the great ice sheets

The changing mass of the great ice sheets of Greenland and Antarctica represents the largest unknown in predictions of global sea-level rise over the coming decades [17]. Anyhow, if these ice sheets start to melt as global warming continues, they may add significantly to the global mean sea level rise. The potential effect of these ice sheets on the sea level as a result of global warming is great. Projections indicate that there is enough water in these ice sheets taken together for a sea level rise of up to 13 metres over the next 1000 years [18, 19].

The last IPCC report expected only a very minor contribution from the melting of ice on Greenland to the sea level rise this century. Nor was it thought that instability in the WAIS would contribute significantly to sea level rise this century [6]. The last IPCC report characterised Antarctica as a sleeping giant with regard to climate change. Recently NASA scientists revealed that Antarctica lost much more ice to the sea than it gained from snowfall, resulting in an increase in sea level [20]. The survey shows that there was a net loss of ice from the combined polar ice sheets between 1992 and 2003 and a corresponding rise in sea level.

In the meantime there have been clear indications of the non-linear course of the process by which these ice sheets disintegrate and that the melting process would therefore probably proceed far faster than has hitherto been supposed (faster than an ice sheet can grow), see Box Greenland has been observed to be melting harder and faster, with an acceleration in the shifting of glaciers after breaking up, and after the thinning of the floating ice sheets bordering the Greenland coast and some parts of Antarctica (West Antarctic Ice Sheet and peninsula). Recently, the spectacular collapse of Antarctica's Larsen B Ice Shelf has been blamed on effects of global warming in the Antarctic Peninsula, which is more pronounced in this region than elsewhere in Antarctica or the rest of the world [21]. Recent indications of these disintegration processes are, amongst other things, a doubling of the frequency of glacial earthquakes (icequakes) during the past 5 years [22] and a doubling of the net loss of ice of the Greenland ice sheet during the period 1996–2005. There are thus indications that the giant is starting to awaken, even though the Eastern Antarctica shows little sign of change at the moment [12].

These new observations lead one to expect a considerably greater contribution from the ice sheets to sea level rise this century than expected by the IPCC [6]. (See also Box). If the global temperature continues to increase, a significant additional contribution is expected from both Greenland and the WAIS to the sea level rise over the very long term (after the 21^{st} century), even in the absence of accelerated melting.

Taking the new evidence on the acceleration of ice-sheet outlet glaciers together with estimates of increasingly negative surface mass balance, yields, according to Rignot and Kanagaratnam [23], a contribution from the Greenland Ice Sheet of more than 0.5 mm/year to global sea-level rise, over two-thirds of which is derived from acceleration. This new information on velocity change more than doubles previous estimates of losses from the ice sheet to the global ocean [17].

The *conclusion* is that, while there are still many uncertainties about the longer term (after 2100), it is nevertheless probable that a global temperature rise of more than $1\ldots2\,^\circ$C will cause irreversible melting of the Greenland Ice Sheet, resulting ultimately in a sea level rise of 7 metres. This process may well take 1000 years or more (unless the positive feedbacks are stronger than expected), but it can start in the course of this century. Overpeck et. al. [24] state that when various disintegration processes are coming into play, a sea level rise exceeding 1m per century can occur, from the end of this century. Because natural variations in the mass balance are large, long term studies are necessary to be able to draw sound conclusions.

Box: Melting of the Greenland Ice Sheet

In some places the Greenland ice sheet is more than 3 km thick. It contains nearly 3 million cubic kilometres of ice. If this enormous quantity were to melt, the global sea level would rise by 7 metres, resulting in the submergence of many coastal regions and most of the world's largest cities [11].

The Greenland Ice Sheet gains mass through snowfall and loses mass by surface melting and runoff to the sea, together with the production of icebergs and melting at the base of its floating ice tongues. The difference between these gains and losses is the mass balance. A negative balance contributes to global sea-level rise and vice versa. Glacier accelerations have been related to enhanced surface meltwater production penetrating to the bed to lubricate its motion, and ice-shelf removal, ice-front retreat, and glacier ungrounding that reduce resistance to flow. The magnitude of the glacier response to changes in air temperature also depends on the glacier-bed properties, geometry, and depth below sea level and the characteristics of the subglacial water storage systems [23].

At annual mean local warming of more than 2.7 °C, the precipitation in Greenland is exceeded by the melting, which leads on balance to shrinkage of the ice sheet [6, 25]. In recent decades the Greenland Ice Sheet seems to have been melting with increasing rapidity [26]. Recent research also suggests that a local temperature increase of a little less than 3 °C (which is associated with a global mean warming of ca. 1.5 °C) may start a process of irreversible melting of the Greenland ice sheet over a period of 1000 years or more [19, 27]. Rignot and Kanagaratnam [23] report that Greenland's mass loss doubled in the last decade, well beyond error bounds. Its contribution to sea-level rise increased from 0.23 mm/year in 1996 to 0.57 mm/year in 2005.

The main reason for Greenland warming up more in the future than the global mean is a positive or self-amplifying feedback, which may even result in a runaway effect (an uncontrollable feedback). Snow and ice reflect more than approximately 85 % of incident solar radiation, which is much more than sea and land. If snow and ice were to decline in Greenland due to warming, a greater area of land and sea will be exposed to the sun, meaning that less solar radiation will be reflected and more absorbed. This will lead to extra warming, leading in turn to the melting of more snow and ice and yet more warming.

An additional effect is the possible significant warming impact on the Arctic by black carbon (soot), generated through the process of incomplete combustion and transported from, for instance, south Asia. It is thought that soot causes Arctic melting because as it settles on ice and snow the surface is darkened, absorbing more sunlight and causing faster melting [28]. Airborne soot also warms the air and affects weather patterns and clouds. Finally, the atmospheric layer that has to warm in order to warm the surface is shallower in the Arctic.

Not much is currently known about the process by which ice sheets disintegrate. The dynamics (and thus the final outflow into the sea) are generally governed by the ice thickness, and its slope and the friction at the base of the glacier. Glaciologists have observed in Greenland that the melt water trickles through the ice sheet to flow out underneath it. This acts as a lubricant: parts of the ice sheet therefore shift faster into the sea [29]. Researchers at the Climate Change Institute in Maine have, in their recent measurements (July 2005), seen that the Kangerdlugssuaq glacier in southeast Greenland is moving at a speed of ca.38 m per day towards the ocean. This speed is nearly three times greater than in the late 1990s. This seems to be one of the fastest moving glaciers in the world. A complication here is that the ice sheets bordering the coast of Greenland (and Antarctica), and closing off the mouths of the glaciers flowing from the mainland, are thinning or even breaking up, which accelerates the flow of the glaciers into the sea. The contribution of Greenland and Antarctica to sea level rise this century is expected to be possibly far greater than was hitherto supposed by the IPCC [6]. It is not yet clear whether the accelerated melting should be ascribed to global warming or natural causes (such as changes in the atmospheric circulation patterns in the northern hemisphere).The climate in Greenland will be far milder without an ice sheet because the land surface will then be far lower than the top surface of an ice sheet and will reflect less sunlight. Even if the values for global climate and the composition of the atmosphere were to return to their pre-industrial levels, the ice sheet would probably not return. This means that the sea level rise will very probably be irreversible.

3. Ocean acidification

Another new phenomenon is the acidification of the oceans due to the increase in dissolved CO_2 concentration [30]. The oceans are absorbing CO_2 from the atmosphere and this is causing chemical changes: a shifting of the carbonate equilibrium and a higher acidity (that is, decreasing the pH), which can bring about several adverse effects.

Carbonate chemistry measurements at the Hawaiian Ocean Time-series (HOT), the Bermuda-Atlantic Time-series (BATS) and the European Station for Times Series in the Ocean at the Canary Islands (ESTOC) show a shift in carbonate equilibrium consistent with increases in atmospheric CO_2. Over the last two decades, several large-scale programs (Joint Global Ocean Survey, World Ocean Circulation Experiment, Ocean-Atmosphere Carbon Exchange Study) have measured the carbonate chemistry along multiple ocean transects [31].

In the past 200 years the oceans have absorbed approximately half the CO_2 emitted through human activities. Calculations based on measurements indicate that this uptake of CO_2 over the past 200 years has led to a reduction in the average pH of surface sea water of 0.1 units and could fall by 0.5 units by the year 2100. This pH is probably lower than has been experienced for hundreds of millennia and, critically, at a rate of change probably 100 times greater than at any time over this period. The study "Carbon Dioxide and Our Ocean Legacy" [32] examined data collected from ocean sampling in the Pacific Ocean from the Southern to Northern hemispheres, confirming that the ocean's daily uptake of 22 million tons of carbon dioxide is starting to take its toll on the chemistry of seawater. At present, ocean chemistry is changing at least 100 times more rapidly than it has changed during the 650 000 years preceding our industrial area. And, if current carbon dioxide emission trends continue, computer models show that the ocean will continue to undergo acidification, to an extent and rates that have not occurered for tens of millions of years.

The acidic water could interrupt the process of shell and coral formation, and adversely affect other organisms dependent on corals and shellfish. The acidity could also negatively impact other calcifying organisms, such as phytoplankton and zooplankton. This may reduce the ocean's ability to absorb CO_2 from the atmosphere, which in turn will accelerate the rate of global warming. The entire marine food chain may also be harmed. Ocean acidification is essentially irreversible during our lifetime. It will take tens of thousands of years for ocean chemistry to return to a condition similar to that occurring in pre-industrial times. CO_2-induced acidification of the marine system has only recently emerged as a serious issue, backed up by experimental studies. Research into the impacts of high concentrations of CO_2 in the oceans is in its infancy and needs to be developed rapidly, given the gravity of this problem.

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