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Climate Projections for the 21st Century

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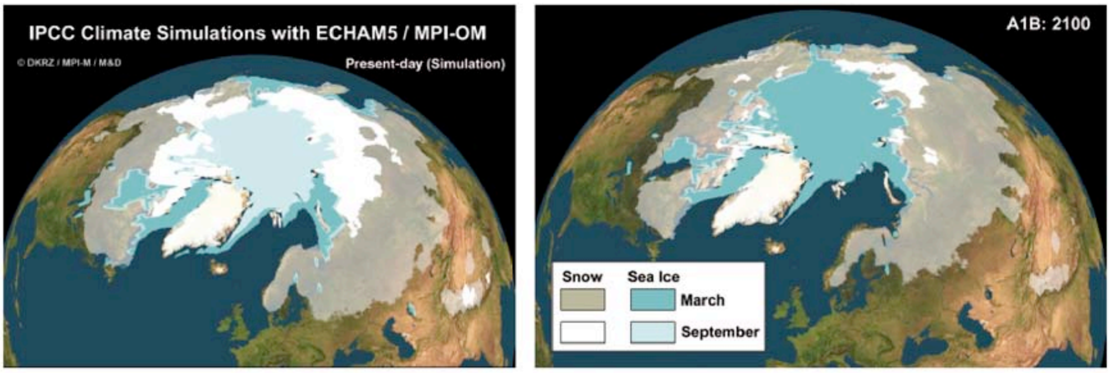

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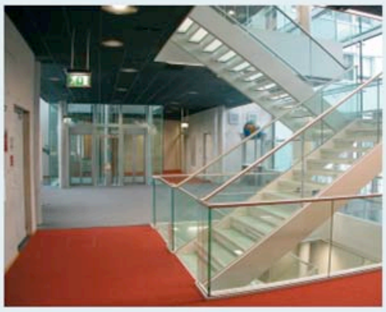

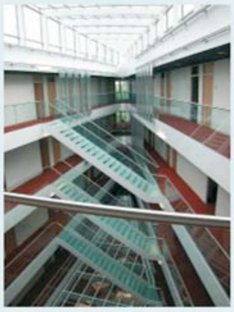

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Summary

Since the middle of the 19th century the temperature of the Earth's surface has increased by almost 1 degree. Much of this observed global warming is due to human activities. Recent climate simulations performed by the Max Planck Institute for Meteorology suggest that the global, annual mean temperature increases by 2.5°C to 4°C at the end of the 21st century if emissions of carbon dioxide and other greenhouse gases continue to grow unabatedly. The most important results of this study are summarized as follows:

- Land areas will warm more rapidly than the oceans. The most notable warming is expected at high northern latitudes, in particular in the Arctic region.
- The precipitation amount tends to increase in humid climate zones (tropics, middle and high latitudes) and decreases in arid climate zones (subtropics).
- The precipitation intensity and risk of flooding increase in most regions.
- In most parts of Europe the snow amount in winter decreases by 80-90% until the end of this century. A decrease by 30-50% is simulated for the Alps and for the Norwegian mountains.
- The length of dry spells increases world-wide. The risk of drying is most pronounced in the Mediterranean countries, in South Africa, and in Australia.
- At the end of this century the contrast between dry and wet climate zones becomes more pronounced, and precipitation extremes of both signs are increasing.
- The intensity of winter storms increases in Central Europa but decreases in the Mediterranean area.
- Due to thermal expansion, the global sea-level rises by 20 cm to 30 cm until the end of this century. The melting of Greenland ice contributes to some 15 cm, whilst enhanced snowfall in Antarctica tends to decrease the global sea-level by 5 cm.
- The pronounced warming of the Arctic leads to thinner sea-ice in winter and smaller sea-ice extent in summer. The observed loss of summer ice in recent years is expected to continue in the climate projections: Until the end of this century the whole Arctic Ocean will become ice-free in summer.
- Higher temperatures and precipitation amounts reduce the density of the surface water in the North Atlantic and, hence, the strength of the thermohaline circulation and the northward heat transport. However, the weakening of the circulation by about 30% until the end of this century has little effect on the European climate, which continues to warm due to higher levels of atmospheric greenhouse gases.
- In the past, the greenhouse warming has partially been 'masked' by increasing atmospheric concentrations of anthropogenic aerosols like sulfate and black carbon. Drastic measures to improve air quality would result in a rapid global warming of almost 1 degree within ten years. Thus, strategies to limit climate warming below a specified threshold need to be reconciled with strategies to reduce air pollution.

Introduction

International agreements such as the Kyoto Protocol establish goals for global environmental policies. The Kyoto Protocol, for example, aims to reduce greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) publishes regular summaries of recent research, in order to support governments in limiting future climate change. This includes projections of possible future climate changes using detailed climate models, based on hypothetical scenarios of CO_2 and other greenhouse gas emissions.

At the end of 2003, climate modelling teams throughout the world were asked by the IPCC to compute three future scenarios. The results of these climate projections are to be made available to other research groups for further evaluation. These evaluations will be published, summarised and reviewed in the Fourth Assessment Report (AR4), due to be published by the IPCC in 2007.

The German contribution consists of a series of simulations, using the climate models of the Max Planck Institute for Meteorology, at the German Climate Computing Centre (DKRZ) in Hamburg. All the 5,000 simulated years needed about 400,000 CPU hours on the supercomputer system for Earth system research at the DKRZ. This requirement constituted one fourth of the year’s computational resources.

The computations were performed with the support of the research group “Model and Data” (M&D), a national service institution, which administers the World Database for Climate Research (WDCC). Since the results of the simulation are of general interest and importance for many research groups, the model data (about 115 Terabyte) are stored in the climate databases of M&D and DKRZ. The results are currently available via internet in the framework of the WDCC to scientists worldwide.

This brochure gives a summary of the emission scenarios prescribed by the IPCC, the different model configurations, as well as the most important results of the climate projections. The authors of this brochure would like to thank all co-workers who have contributed to this project.

The IPCC-Process

In the last decades, the international scientific community has expressed concerns about the impact of human activities on the Earth's climate. Already at the early stage of research, scientists were rapidly convinced of the need to analyze the potential effect of human activity on the climate. This was the objective assigned to the IPCC (Intergovernmental Panel on Climate Change), set up in 1988 under the joint auspices of two organizations belonging to the UN, UNEP (United Nations Environment Program) and the WMO (World Meteorological Organization).

Right from the start, the IPCC focused on three distinct areas. Group I deals with the scientific aspects of climate change. Group II's task is to examine the consequences of climate change, and to analyze our vulnerability to it and the measures that can be taken to adapt to it. Group III focuses on measures to reduce its effects. To date, three complete reports have been published, the first in 1990, the second in 1995 and the third in 2001. The fourth report, which is still being written, is expected to come out in the fall of 2007.

Each individual report is divided into chapters, and the first draft is entrusted to a team of 10-15 researchers from various countries. In order to carry out this task, each writer seeks contributions from researchers involved in the field concerned. On the basis of these extremely voluminous reports (around a thousand pages) summaries of about fifty pages are drawn up, as well as „Summaries for decision-makers", which are much shorter and written in an accessible style. The whole set of documents is completed by a synthesis report. Once drawn up, the various documents are reviewed by the scientific community and by representatives of government bodies. The writing and review process always takes over two years, to ensure that the text that is put before governments enjoys the approval of the scientific community, which plays a large part in this process.

The prediction of climatic warming connected to human activity is based on a hierarchy of models, ranging from the simplest to the most complex, the coupled ocean-atmosphere models, which enable its geographical distribution and characteristics to be predicted. It is on the basis of this modelling approach that the latest IPCC report (2001) predicts an average warming of between 1.4 and 5.8°C by 2100. The degree of warming depends both on the emission scenario for greenhouse gases and aerosols and on the nature of the models.

The Fourth Assessment Report (AR4) will show a substantial progress in modelling. This applies to the models themselves and the number of participating institutions (worldwide 15, the Max Planck Institute for Meteorology being amongst them). It also applies to the scope of computations, which by now have been finished and for the most part have been evaluated.

Emission Scenarios

The emission scenarios developed through the IPCC for the years 2001-2100 are based on different assumptions of demographic, social, economic and technological change. The emission scenarios A2, A1B and B1, chosen for the fourth assessment report of the IPCC, are based on the following socio-economic assumptions:

Scenario family A2 describes a very heterogeneous world. The birth rates in the different regions are only slowly converging, leading to a continuous rise of the world's population. Economic growth is mainly regional and economic growth per capita, as well as technological change, will be slower and more fragmented than in other scenario families.

Scenario family A1 describes a future world with very rapid economic growth and a world population that will grow until the middle of the 21st century and subsequently decrease, accompanied by the advent of new and more efficient technologies. The three A1-groups differ in respect to their technological emphasis: intensive use of fossil fuels (A1FI), non-fossil sources of energy (A1T) or balanced use of all energy sources (A1B).

Scenario family B1 describes a world with the same global population as in scenario A1 but with rapid changes in the economy, moving towards a service and information oriented society with far less natural resource usage and the introduction of environmentally friendly technologies. Society's emphasis is given to finding global solutions for economic, social and ecological sustainability, including greater social justice, but without additional climate protection initiatives.

Based on these specifications, an IPCC working group created emission scenarios for the most important greenhouse gases and aerosols (examples in Table 1). Using biogeochemical models, the respective atmospheric concentrations were then computed as input for the climate models. Figure 1 shows the temporal evolution of the CO_2 concentration, from 1860-2000 (observed) and 2001-2100 (scenarios A2, A1B and B1). During the last 650,000 years up to the start of the industrial revolution, the CO_2 concentration in the atmosphere varied between about 200 and 300 ppmv (parts per million by volume). In comparison, even in the relatively "favourable" B1 scenario the pre-industrial value of 280 ppmv will almost double to 550 ppmv by the end of the 21st century.

In addition to CO_2, methane (CH_4), nitrous oxide (N_2O), ozone (O_3), the most important chlorofluorocarbons (CFC's), as well as sulphate aerosols (SO_4), which are produced upon atmospheric oxidation of sulphur dioxide (SO_2), are being considered.

	CO_2-Emissions (PgC/Year)			SO_2-Emissions (TgS/Year)		
Year	A2	A1B	B1	A2	A1B	B1
2000	8	8	8	69	69	69
2020	12	13	11	100	100	75
2040	16	15	12	109	69	79
2060	19	16	10	90	47	56
2080	23	15	7	65	31	36
2100	29	13	4	60	28	25

Table 1. Emissions of carbon dioxide (CO_2) and sulphur dioxide (SO_2) from fossil fuels, industrial activities and changes in land use in the IPCC scenarios A2, A1B and B1. 1 Petagram of carbon (PgC) = 1 billion tonnes of carbon. 1 Teragram of sulphur (TgS) = 1 million tonnes of sulphur.

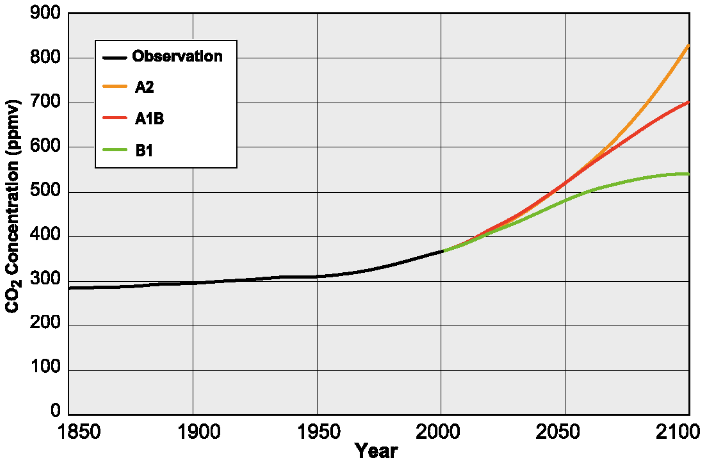

Figure 1. CO_2 concentration, both observed (1850-2000) and as prescribed for the IPCC scenarios A2, A1B and B1. Units: ppmv = parts per million by volume.

The Climate Models of the Max Planck Institute for Meteorology

Climate models serve as theoretical tools for research into the complexities of the climate system. They are the only “language” in which we can express these processes, both qualitatively and quantitatively.

The German IPCC computations were done with global climate models from the Max Planck Institute for Meteorology. The base model (short: IPCC model) consists of two main components: the atmosphere and the land surface model ECHAM5 and the ocean model MPI-OM (Fig. 2). The horizontal resolution of the atmosphere model is 1.875°, corresponding to a grid distance of about 200 km at the equator. The ocean model has a horizontal resolution of 1.5° corresponding to about 160 km at the equator. The model contains the processes that are resolved by the grid, as well as unresolved or “parameterised” processes, which are important for the transport of momentum, energy and water in the Earth system.

The IPCC model is the physical-dynamical core of two more complex models. The detailed simulation of aerosols on the one hand (Fig. 3) and the added consideration of the carbon cycle on the other (Fig. 4), allows the computation of climate change with anthropogenic emissions as input (CO_2, SO_2, soot particles and other carbonaceous aerosols). Their respective atmospheric concentrations are then computed internally within these models. In contrast, the IPCC model uses externally calculated concentrations as their prescribed input values.

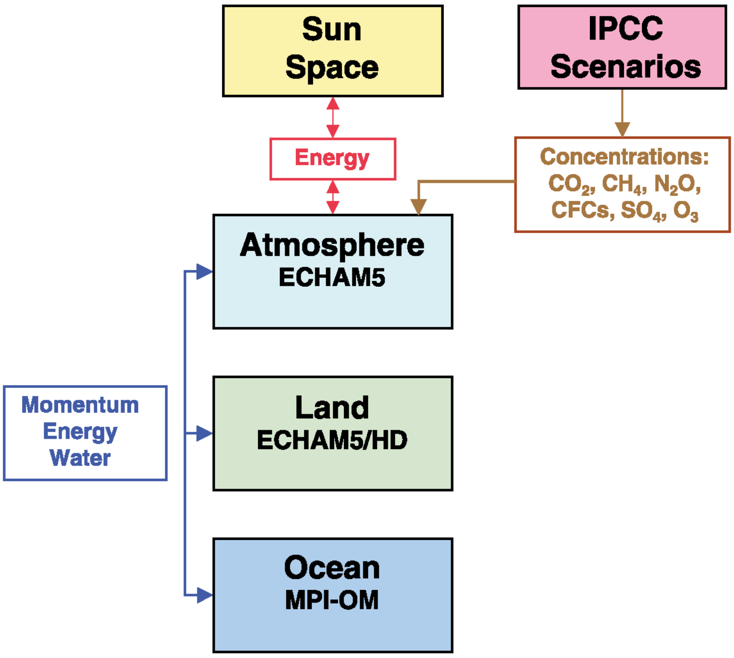

Figure 2. Schematic representation of the IPCC climate model. The ECHAM5 model contains atmosphere and surface models including a hydrological discharge model (HD), the MPI-OM contains the oceans including a sea-ice model. Apart from the anthropogenic impacts, natural climate-relevant processes such as volcanic eruptions and variations in solar radiation can be considered.

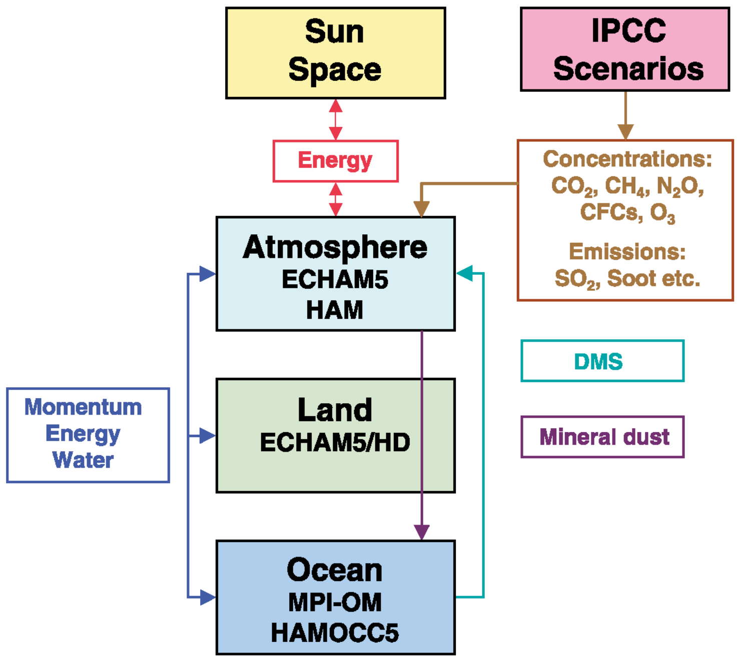

Figure 3. IPCC model (Fig. 2) including a detailed aerosol model (HAM) and marine biogeochemistry model (HAMOCC5). The input of mineral dust into the ocean, as well as marine dimethylsulphide (DMS) into the atmosphere, is calculated by the model. DMS is a metabolic product of phytoplankton and influences the atmospheric sulphur cycle. Anthropogenic emissions of SO_2 and soot, as well as other aerosols, are prescribed externally.

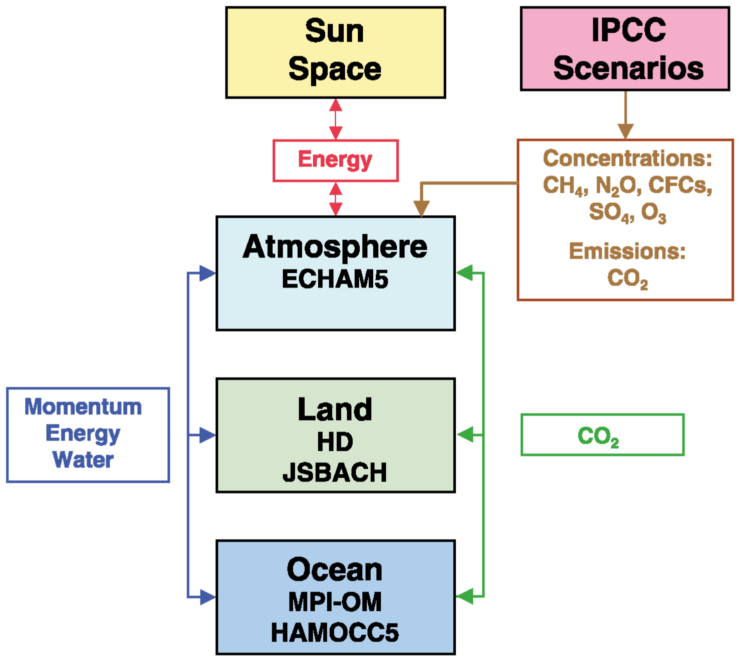

Figure 4. IPCC model (Fig. 2) including the carbon cycle. The model includes a vegetation and surface model and the terrestrial carbon cycle (JSBACH), as well as a marine biogeochemistry model (HAMOCC5). The exchange of CO_2 between the atmosphere, surface, vegetation and ocean, as well as the storage of carbon in these reservoirs, is calculated within the model. The input of CO_2 into the atmosphere due to combustion processes and changes in land use is prescribed externally.

The evaluation of a climate model usually runs in two steps. Firstly, the respective model components (atmosphere, ocean, etc) are developed and optimized. Atmospheric models, for instance, are forced with observed conditions of the 1980´s and 1990´s (sea surface temperature, sea-ice). The simulated and observed climates of those years are then compared. Secondly, the coupled models are then tested over several centuries of simulation. The stability of the climate is of importance, as well as those phenomena that are directly dependent on the coupling process, such as the seasonal sea-ice distribution or El Niño/La Niña oscillations in the Tropical Pacific. The IPCC model (Fig. 2) was used for a simulation over 500 years with constant pre-industrial concentrations of CO_2 and other greenhouse gases. Under these conditions, nearly trend-free climate behaviour can be expected. Indeed, the global surface air temperature in this 500-year simulation rises insignificantly by about 0.03 degrees Celsius per century (Fig. 5). This simulation of the pre-industrial climate provides the initial values for the simulation of the climate in the 20th century and the following climate projections for the 21st century.

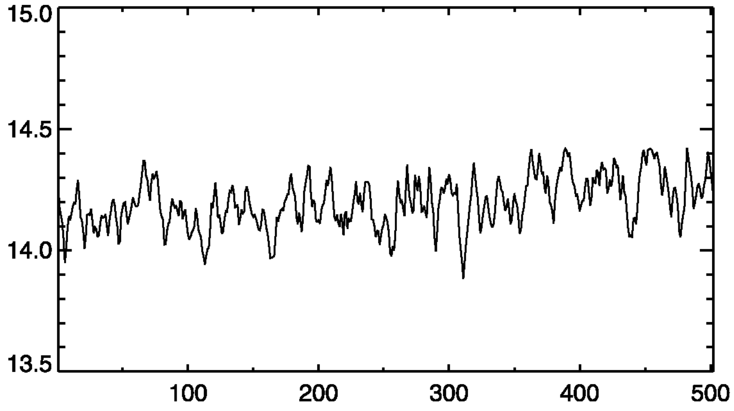

Figure 5. Time series of global, annual mean surface air temperature (°C) in a climate simulation with the IPCC model (Fig. 2) under constant pre-industrial conditions (composition of the atmosphere and solar radiation). There are no references to the calendar years in the time axis. Each model year represents a possible pre-industrial state of the atmosphere and the ocean (here: year 1860).

A further standard test consists of finding out if the model is capable to reproduce the observed climatic trend of the 20th century due to the observed external input of greenhouse gases, aerosols, solar radiation and volcanic eruptions. It has to be taken into account that the interannual temperature oscillations are caused by internal processes (Fig. 5) and can be traced back mainly to El Niño and La Niña events. These natural oscillations cannot be simulated in the observed order of occurrence, but can only be reproduced in their statistical properties (frequency, amplitude, etc). Longer lasting trends due to changes in external inputs (CO_2 increase), but also abrupt changes in temperature following strong volcanic eruptions, can be reproduced by the models. Figure 6 shows that both models (Fig. 2 and 3) are able to reproduce the observed temperature trend in the 20th century, however they overestimate the cooling of the Earth's surface after major volcanic eruptions, particularly after the eruption of Krakatoa in 1883 - presumably due to the large uncertainties in the amount of emitted sulphur.

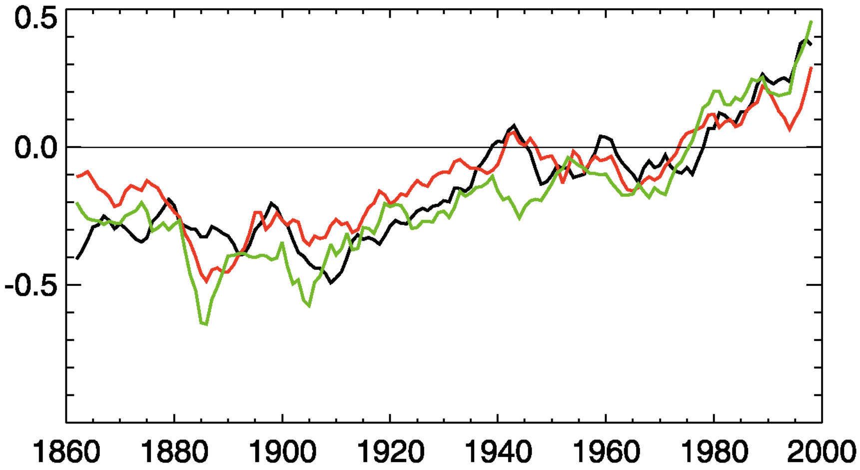

Figure 6. Time series of the global, annual average of observed and simulated surface air temperatures (°C) shown as a difference from the average of the years 1961-1990. Black: observed, red: IPCC model (Fig. 2), green: IPCC model including interactive aerosols (Fig. 3). In both simulations, natural external forcing (volcanic eruptions, solar variability) as well as anthropogenic activities (emissions of CO_2 and other greenhouse gases, as well as aerosols) are being considered.

Results of the Climate Projections

Temperature and Precipitation

The increase of greenhouse gases and changes in sulphur emissions lead to a global warming in the IPCC model (Fig. 2), which by 2100 will reach values between 2.5 °C (B1) and 4.1 °C (A2) (Fig. 7). These figures are relative to the average of the years 1961-1990. Considering the different CO_2 concentrations in A2 and A1B the degrees of warming are unexpectedly similar, with A1B showing an increase of 3.7 °C. The reason for this is that in the second half of the 21st century, the cooling effect of sulphur aerosols will decrease considerably faster in A1B than in A2 (Table 1). Thus, the warming in A1B caused by the decreased sulphur emissions is greater than in A2 and partly compensates the weaker CO_2 increase in A1B (Fig. 1).

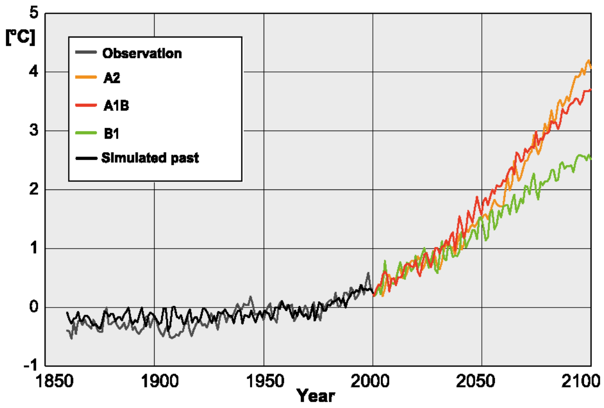

Figure 7. Time series of the changes in global and annual average surface air temperature, relative to the mean values of the years 1961-1990. In contrast to Fig. 6, natural events such as volcanic eruptions and changes in solar irradiation between 1860-2000, have not been taken into account.

Figure 8 shows the geographical distribution of annual temperature changes for scenarios A1B and B1. In both scenarios the continents warm faster than the oceans. The warming is strongest in higher northern latitudes where the amount of snow and sea-ice decreases. The bright ice and snow areas give way to relatively dark water and snow-free land areas. Thus, a larger part of solar radiation will be converted to heat, which causes the temperature to rise further. This effect – the so-called 'Ice Albedo Temperature Feedback' - is the main reason for extreme changes in temperature in high northern latitudes. The oceans warm more slowly than the land surfaces, because vertical mixing processes distribute the extra heat over larger volumes. These vertical mixing processes are especially efficient in the North Atlantic and in the Southern Ocean, hence the lowest degrees of warming are simulated there.

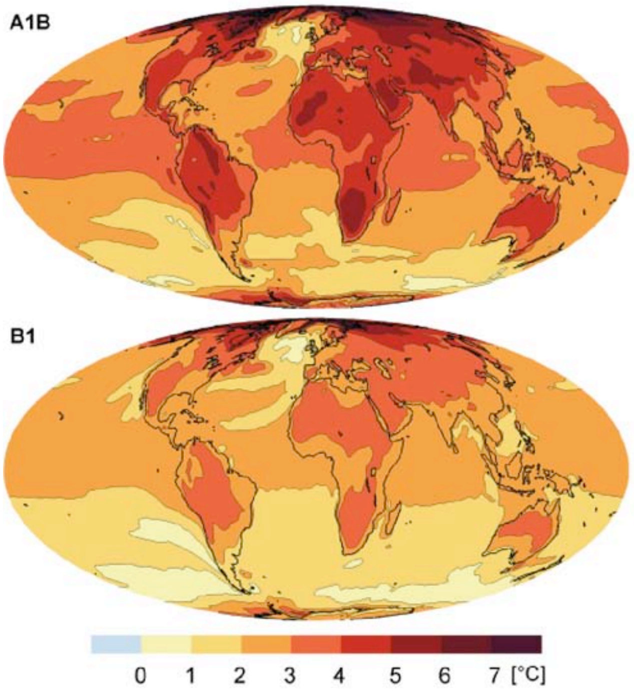

Figure 8. Changes in surface air temperature in scenarios A1B and B1. Shown is the difference of the 30 year average 2071-2100 from that of 1961-1990.

The direct effects of global warming result in higher evaporation rates and consequently in greater precipitation. Figure 9 shows an increase in annual precipitation for all three scenarios. By 2100 the global average precipitation see an increase between 5% (B1) and 7% (A2, A1B), compared to the average values of the period 1961 to 1990. Greater precipitation will occur particularly in the equatorial regions and higher latitudes (Fig. 10). Less precipitation will occur, above all, in the subtropics (Mediterranean region, South Africa, Australia and the subtropical ocean regions). This will result in an intensification of the contrast between dry climate zones (subtropics) and wet climate zones (tropics, middle and high latitudes).

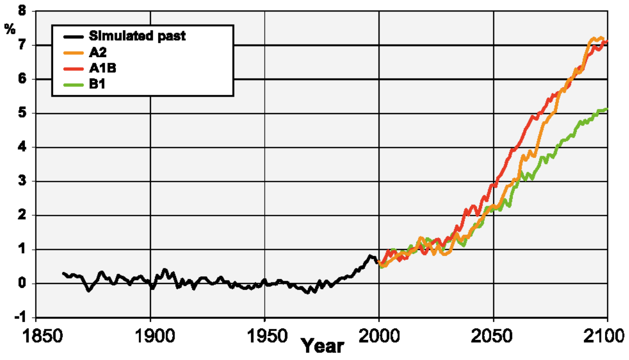

Figure 9. Time series of global, annual mean change in precipitation (%) relative to the average of the years 1961-1990.

The changes in precipitation in Europe and other regions (e.g., South America and Central Africa) are closely connected to the seasonal shift of the climate zones. The simulation shows that there will be a sharp decrease in winter precipitation in the Mediterranean. In summer, this anomaly will migrate northwards, affecting parts of Southern and Central Europe. In Central Europe and especially Scandinavia, precipitation will increase in winter.

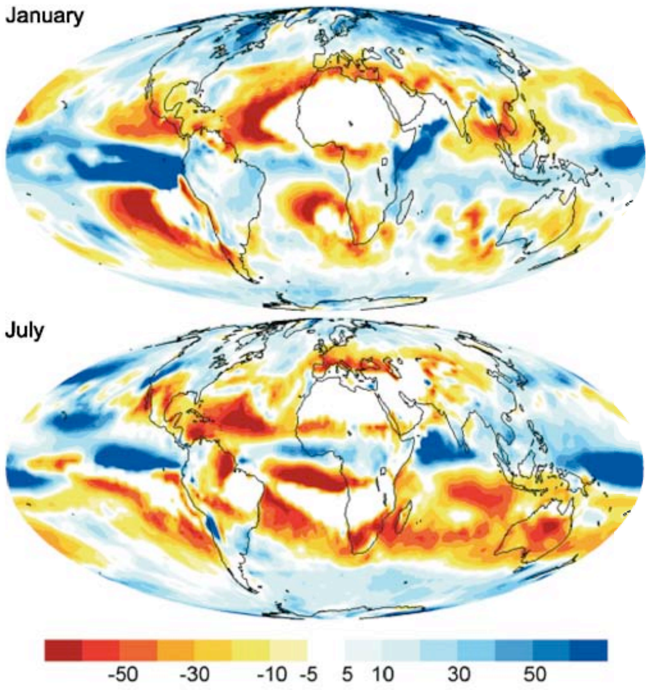

Figure 10. Changes in precipitation for January and July in scenario A1B. Shown are the relative changes (%) between 2071-2100, compared to average values of the years 1961-1990.

Sea-level, Sea-ice and Ocean Circulation

Within the climate system, the important role of the ocean results from its function as a storage and transfer medium for heat and matter (salt, carbon, etc.). Compared to the atmosphere, the ocean has a much greater heat capacity. Great parts of the ocean in high latitudes are covered with sea-ice, which inhibits the exchange between atmosphere and ocean and represents a large fresh water reservoir.

One of the immediate effects of global warming on mankind will be the rise of sea-level, to which the following factors will contribute:

a) Changes in volume due to changes in water density
b) Changes in volume of continental ice sheets and glaciers
c) Changes in the ocean circulation.

By the year 2100 the global sea-level will rise, due to warming (mechanism a) by 0.21-0.28 m (Figure 11), depending on the scenario. In addition to this global sea-level rise, changes in the oceanic circulation will result in both positive and negative regional anomalies: The eastern North Atlantic, for example, is expected to undergo a further rise of 0.2 m, giving a total rise in the North Sea of about 0.5 m. The intensification of the hydrological cycle (more evaporation in lower latitudes and more precipitation in higher latitudes) causes a change in the ocean's salinity and thus affects the density of the water and its volume. In the Arctic, this effect contributes markedly towards a rise in the sea-level, while a decrease is expected in tropical regions. The regional differences in the change of sea-level up to the year 2100 can be seen clearly in Figure 12; sea-level change ranges from a small decrease in the Southern Ocean to local rises of more than a metre.

The contribution resulting from the changes in land-ice volume (mechanism b) can be estimated by the snowfall and melting rates in these regions. Until the year 2100, scenario A1B shows an added global average sea-level rise of about 8 cm. This is the result of two factors: The melting of Greenland ice, contributing to a rise of 13 cm and the increased snowfall in the Antarctic, resulting in a lowering of 5 cm.

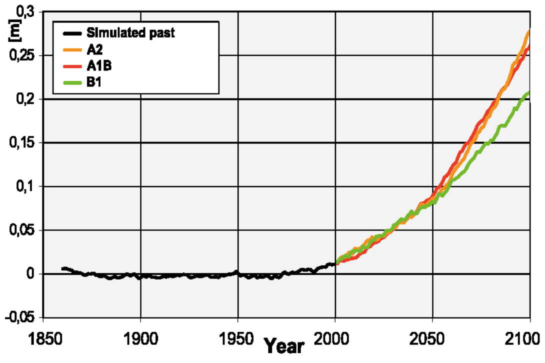

Figure 11. Time series of the global mean sea-level in scenarios A2, A1B and B1, relative to the average of the years 1961-1990.

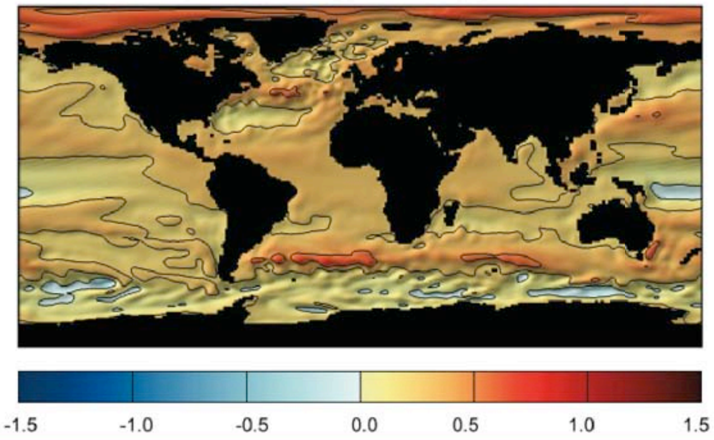

Figure 12. Changes in the global mean sea-level (m) by the year 2100, relative to the year 2000 for scenario A1B.

Since the beginning of satellite monitoring in 1978, the Arctic summer sea-ice extent has decreased by about 8% per decade; this trend has increased in recent years. The average sea-ice extent in September of the last four years was 20% less than that of the years 1978-2000; in September 2005 the reduction amounted to over 25%. The decrease corresponds to an area of about five times the size of Germany. In 2005 the so-called North-East Passage, the sea route along the Siberian coast, was ice-free from the 15th of August to the 28th of September. The trend of decreasing ice extent in summer is also evident in the climate projections (Figure 13). Scenarios A2 and A1B show the Arctic free of ice in summer towards the end of the 21st century, while according to scenario B1, some ice will still remain (Fig. 14). The melting will cause distinctive changes, as well as threaten the Arctic's ecosystem. The sea-ice around the South Pole is also melting and its extent is decreasing. However, the lesser degree of warming experienced by the Southern Ocean (Fig. 8) will result in a lesser rate of melting than in the Arctic.

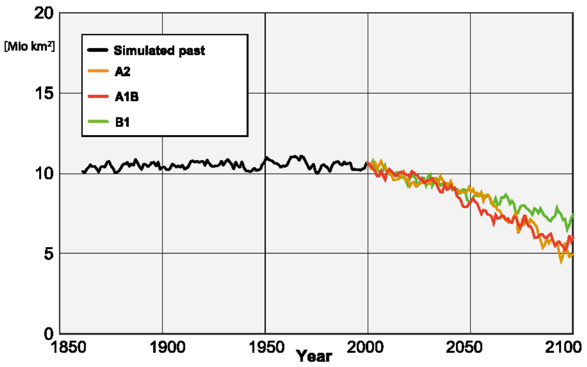

Figure 13. Time series of the area covered by sea-ice in the northern hemisphere, as an annual average for scenarios A2, A1B and B1.

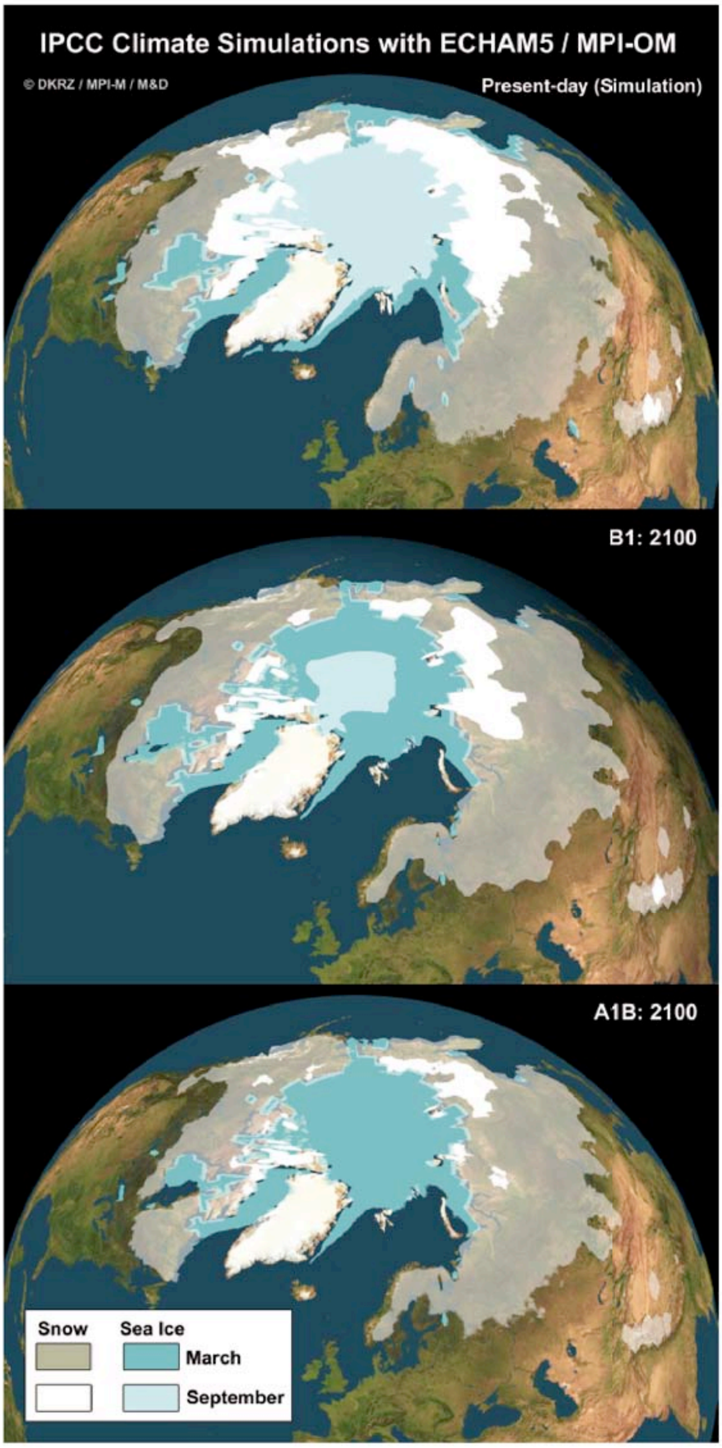

Figure 14. Comparison of present-day sea-ice extent in March and September (above), with the projections for scenario B1 (middle) and A1B (bottom) for the year 2100. Also shown are the areas of land snow extent.

The large-scale ocean circulation in the Atlantic plays an important role for the climate in Europe. The so-called thermohaline circulation transports warm near-surface water from the tropics to the north and cold deep water to the south. A decrease in density of surface water in the high latitudes caused by warming or by increased fresh water input, resulting from higher precipitation rates (as is expected in a warmer climate), would disturb this overturning circulation and at worst, cause it to collapse.

Such breakdowns in the thermohaline circulation did occur in the past. For the 21st century, our climate simulation show a marked reduction in the thermohaline circulation resulting from global warming; however no total breakdown is simulated. By the year 2100, a decrease of up to 30% is expected (Fig. 15). The weaker rate of heat transfer opposes the general warming: In the North Atlantic there will be only slight warming, while a slight cooling will occur near Greenland. Further model experiments predict no breakdown of the thermohaline circulation even in case of substantial melting of the Greenland ice sheet.

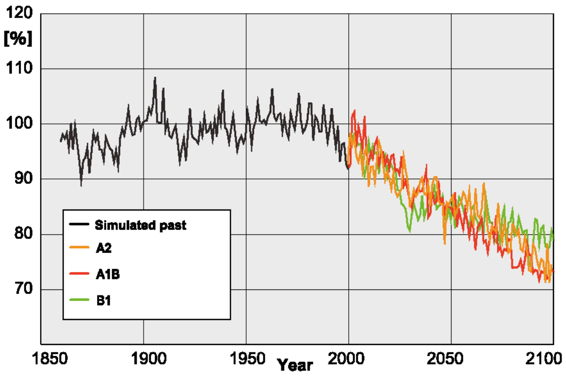

Figure 15. Time series of the thermohaline circulation in the North Atlantic (shown is the intensity as a percentage of the average value of the years 1961-1990).

Weather Extremes

Extreme weather events are very rare events, with an above average intensity that have far-reaching effects on nature, man and the economy. According to Munich RE, the socio-economic damage caused by weather extremes has increased drastically in the last decades. Factors such as increased population, especially within metropolitan areas, as well as the rising standard of living and levels of technology (which are more vulnerable to extreme weather) can result in increasing damages. Analyses of long-term climate data should show if the increased liabilities faced by insurance companies have been caused by more frequent and/or intensive weather extremes. Past climate model simulations (Fig. 6), as well as IPCC climate projections, supply a vast amount of data, which should provide insight into possible changes in weather extremes.

Unlike the very rare 'century events', such as the hot European summer of 2003, trends in modest extremes occurring once a year, for example, can be detected with some confidence. To simplify the comparison of global data and the analysis of weather extremes, indicators for intensive temperature and precipitation events were introduced. They describe moderate weather extremes, which take place at larger temporal and spatial scales. Therefore, they are also suitable for use in global climate models.

These models can identify within their coarse horizontal resolution of 100 to 200 km only long lasting and large–scale events, e.g., heavy precipitation lasting several days, causing flooding, or heat waves affecting several countries. In strongly orographically shaped regions or for extremes affecting smaller areas, one should consider regional models with finer resolution or statistical downscaling techniques.

Global observational data of the last 50 years generally show an increase in night temperature and longer heat waves, a decrease in 'frost days', as well as an increase in 'wet days' and in the maximum five day precipitation events during a year. Computations of the aforementioned indicators with the IPCC climate model confirm these changes for the 20th century. In the climate projections for the 21st century the trends continue, becoming more pronounced in the more extreme A2 and A1B scenarios than in B1. Figures 16 and 17 show the changes of two precipitation indicators, the maximum five day precipitation events during one year (Fig. 16) and the maximum duration of a dry period in a year (Fig. 17). Both indicators represent the values at the end of the 21st century (2071-2100) relative to the average values of the years 1961-1990. In many parts of the Earth, the maximum five day precipitation increases and, therefore, the dangers of flooding also increase. This trend in Europe is especially pronounced in the winter months. At the same time, increases in the maximum duration of dry periods in the course of a year occur especially in Central and Southern Europe, as well as in the lower latitudes (Central America, Brazil, Southern Africa and Australia). In addition to the changes in the average amount of precipitation (Fig. 10), there will also be an increase in extreme weather events. Heavy precipitation will play a bigger part in the average precipitation, while at the same time, intervals between precipitation events will grow.

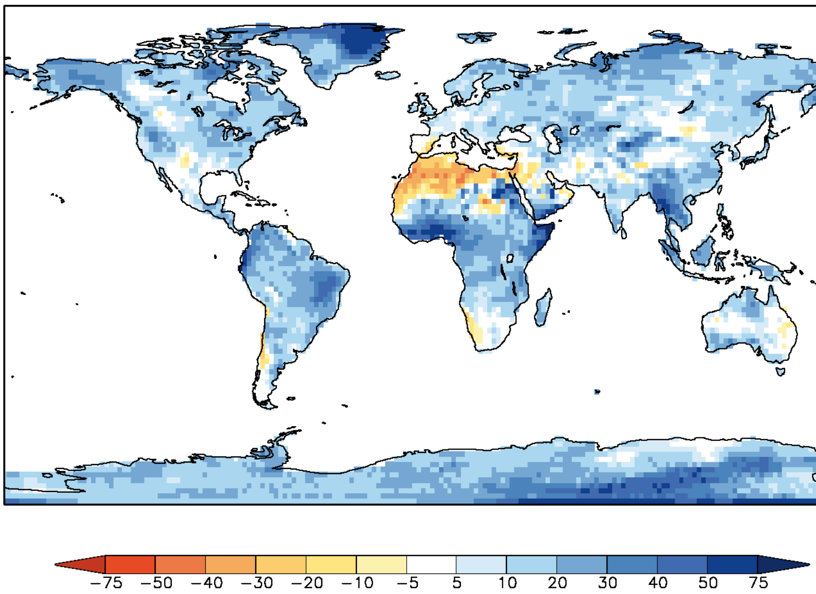

Figure 16. Percentage change of annual extreme precipitation for scenario A1B. The annual extreme precipitation is defined as the maximum amount of precipitation in a five-day period, within a year. Shown is the change in percentage of the 30-year average between 2071-2100, in relation to the average of the years 1961-1990.

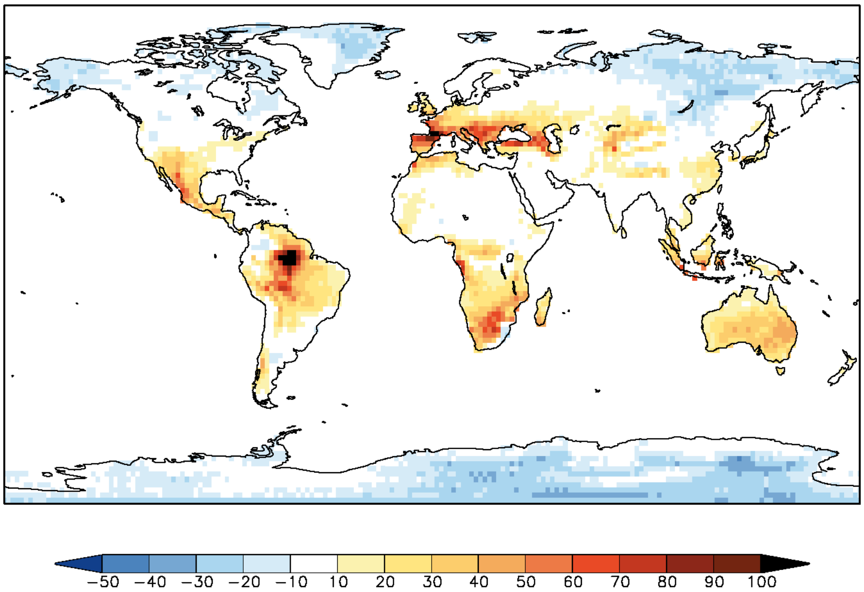

Figure 17. Percentage change of maximum dry periods for scenario A1B. A maximum dry period is defined here as the maximum number of continuous days within a year, with a daily precipitation under the threshold value of 1 mm. Shown is the change in percentage of the 30-year average between 2071-2100, in relation to the average of the years 1961-1990.

As expected, in warmer climates the duration of heat waves increases. In the 20th century a heat wave in Europe with temperatures of at least 5°C above the monthly average lasted about 10 days on average. By the end of the 21st century, according to scenario A1B, the average duration will be over 60 days. Temperatures, as experienced in the European summer heat wave of 2003, will become normal.

The hurricane season of 2005 has dramatically shown the damaging potential of extreme tropical storms. Whether these storms will increase in frequency and/or strength in a warmer climate with higher ocean temperatures is still a matter of scientific debate. One of the sources of uncertainty results from the grid size of current climate models (typically 100 to 200 km), which is not sufficient to realistically simulate tropical storms. The total number of storms is systematically underestimated in climate models, and hurricanes with wind speeds of more than 118 km/h cannot be simulated. The climate projections for the 21st century show a decrease in the frequency and a slight increase in the strength of tropical storms due to increased global warming. However, these predictions do not necessarily apply to hurricanes for the aforementioned reasons.

In contrast to tropical storms, extratropical storms can be realistically simulated in their statistical entirety. This applies to the stormtracks, the total number of storms, their seasonal variation and especially to their frequency in relation to their wind speed. Climate projections for the 21st century predict a decrease in the total number of storms with increased warming. According to the simulations, a slight increase is noted regarding extreme storms, however these changes vary very much regionally.

In Central Europe the average strength of winter storms will increase by about 10%, while the pluvial winter storms in the Mediterranean will significantly decrease in number and strength. These are the main reasons for a reduction in winter rainfall (Fig. 10) and prolonged dry periods (Fig. 17) in the respective areas.

Climate Change in Europe

In order to investigate the effects of global climate change upon Europe, a high-resolution regional climate model (REMO) was embedded into the global IPCC model (Fig. 2). In analogy to using a magnifying glass, it is possible to examine this region in detail and find links between global climate change and it regional consequences.

At the lateral boundaries of the chosen region, the climate variables supplied by the IPCC model (wind, temperature etc.) were prescribed every 6 hours, in addition to the sea surface temperature calculated by the IPCC model. Inside the model domain, the regional climate was computed using the input of the global IPCC model at the lateral and lower boundaries and local geography within the region. The model results are similar to those of the global model in the regional mean. The higher grid resolution better represents the structure of the land surface (mountains and vegetation) than the global model. This includes all processes that are influenced directly by the structure of the land, e.g., cloud formation and precipitation. A high grid resolution is especially favourable for the simulation of local weather extremes, such as heavy summer rainfall.

At the moment REMO is run with two grid sizes: 50 km for Europe and 10 km for Germany. This way, the variations in climate changes can be shown for Northern, Central and Southern Europe, while in Germany, fine-scale structures such as the low mountain ranges, the Oberrheingraben or the Thüringer Becken can be included into the simulations. In scenario A1B an increase in the annual mean surface air temperature of 3.5°C by the year 2100 is predicted for Germany, while the average annual precipitation will hardly change.

Because of the warming, a greater part of winter precipitation will fall as rain. In many parts of Germany the average snow height in January in scenario A1B will decrease by more than 80% by the end of the 21st century. In the higher altitudes of the Alps and in the Norwegian mountains, a reduction of 30-50% is expected (Fig.18). The retreat of the snow is especially clear to see for regions with more than three snow days in January (Fig. 19, inside red line for current climate and inside white line for the period 2071-2100).

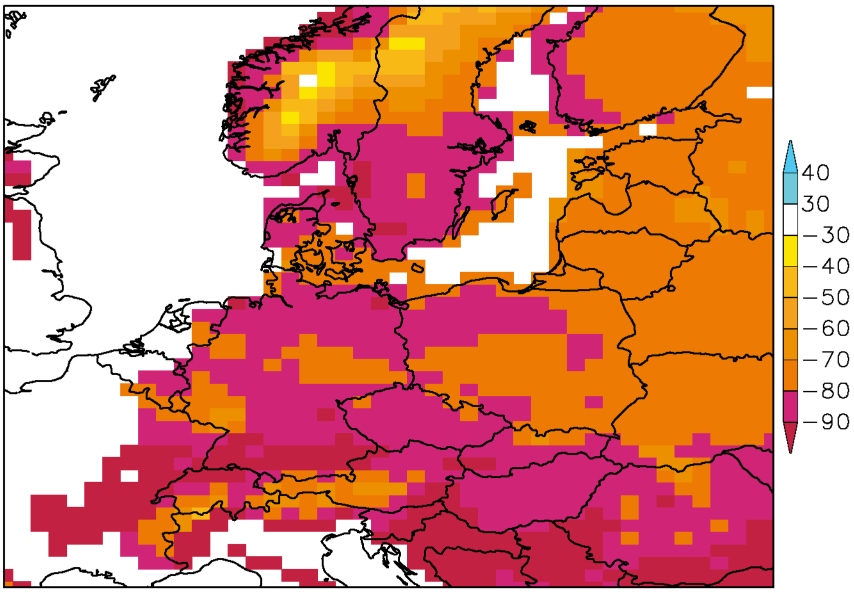

Figure 18. Change in the average snow height in January in scenario A1B. Shown is the relative change in percentage for the time period of 2071-2100 in relation to the average of the years 1961-1990.

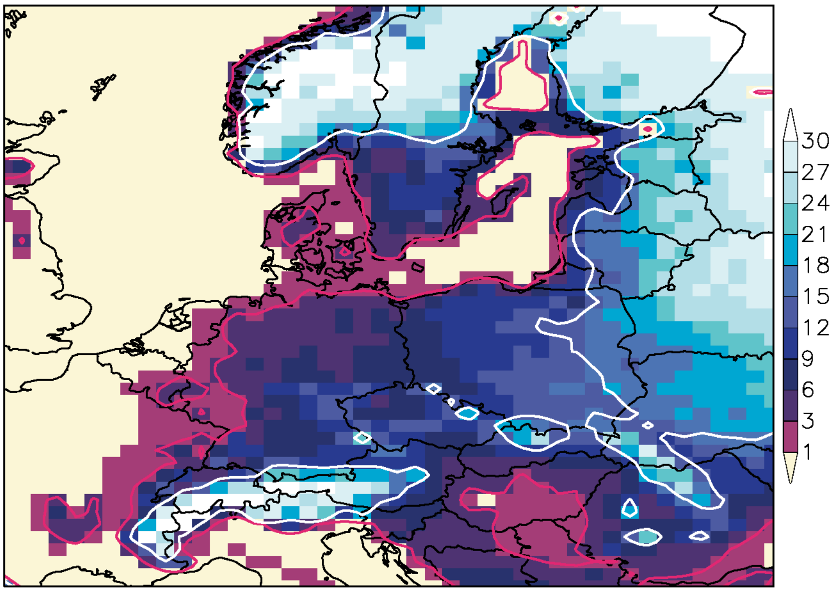

Figure 19. Average number of "snow days" in January for the time period 1961-1990. One snow day is defined as a day with a minimum snow height of 3 cm. The area with more than three snow days in January is enclosed within the red line. In scenario A1B (time period: 2071-2100) the area shrinks to that enclosed by the white line.

The Role of Aerosols

Aerosols are solid or liquid particles in the air with a typical size between 0.01 and 10µm (1 µm = 1 millionth of a metre). In contrast to the greenhouse gases, aerosols have a very short lifetime of only a few days. Aerosols may have natural or anthropogenic origins (sea salt, mineral dust, sulphate, soot, etc.) and influence the climate through complex interactions. Their direct influence stems from their ability to scatter and absorb solar radiation. Indirectly they affect the climate by acting as condensation nuclei, thus altering the optical properties and lifetimes of clouds. An increase in aerosols will induce climate cooling and likewise their reduction will result in global warming.

This is shown very clearly through a sensitivity study with the IPCC model (Fig.2), in which through omitting the anthropogenic sources from year 2001 onward, the atmospheric sulphate concentration immediately returns to its pre-industrial (natural) level. The additional radiation available results in a rapid global warming of about 0.8 °C within just 10 years (Fig. 20). This example shows that to this date, the anthropogenic greenhouse effect has been significantly masked by an increase in aerosol concentration. Since a reduction of air pollution is advisable for health reasons, the additional global warming can only be compensated by an equivalent reduction of greenhouse gas emissions.

If both the concentrations of greenhouse gases and aerosols are maintained at the level of the year 2000, global warming will continue at a rate of about 0.3 °C over the next 100 years, as a result of the inertia of the climate system (Fig. 20, blue curve).

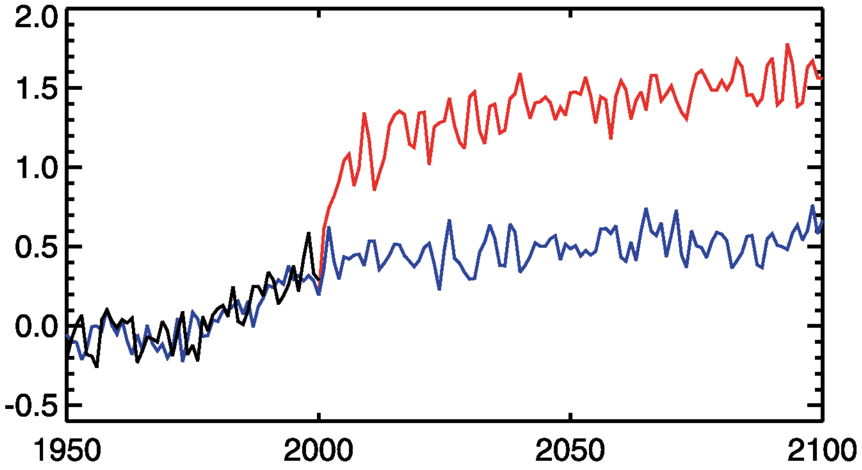

Figure 20. Sensitivity experiment with the IPCC model. Shown is the time series of the global, annual mean surface air temperature (°C) as deviation from the average of the years 1961-1990. Black: observed; blue (1950-2000): Model simulation using observed concentrations of greenhouse gases and aerosols; blue (2001-2100): Continuation with the respective concentrations from the year 2000; red: Continuation with the greenhouse gas concentration from the year 2000 and pre-industrial (natural) aerosol concentration.

The Carbon Cycle and Climate

The future rise in the concentration of atmospheric CO_2 does not solely depend on an increase in anthropogenic CO_2 emissions, but also on the storage capacities of the vegetation, the soil and the ocean. Presently, these reservoirs absorb about 50% of the anthropogenic CO_2 emissions. Whether this uptake capacity will change in a warmer climate can only be tested with the help of models. The direct influence of increasing CO_2 concentrations on the uptake rates of vegetation (CO_2 fertiliser effect), on the Earth's surface and the ocean has to be distinguished from the indirect influence of global warming, which will accelerate both plant respiration and bacterial decomposition process in the soil.

In order to separate these two processes, two simulations were undertaken. In the first, the effect of global warming resulting from the CO_2 increase was considered; in the second, this was artificially suppressed. The model consists of the atmosphere, the ocean and the land, extended to the marine biogeochemistry and land vegetation (Fig. 4).

Figure 21 shows the increase in carbon through anthropogenic emissions for scenario A2 (Table 1). The most important result is that the global warming up to the end of the 21st century is responsible for an additional 200 Gt of carbon in the atmosphere. Since warming has hardly any affect on the amount of carbon in the ocean, this extra 200 Gt is generated by land processes, specifically in the tropics. Here, warming will increase bacterial decomposition processes in the soil, thus reducing the net carbon storage capacity of the land surface by about 25% by the year 2100.

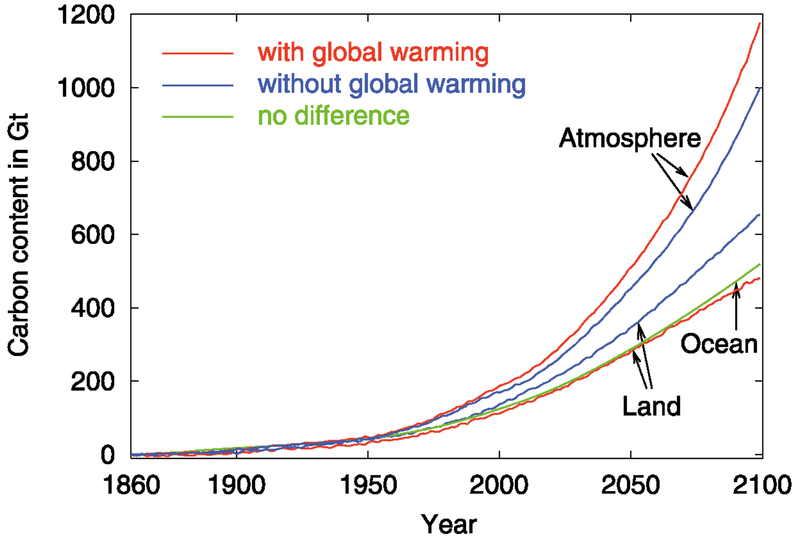

Figure 21. Change in the amount of carbon through anthropogenic emissions, relative to the pre-industrial amount (year 1860) in the atmosphere, on the land (soil and vegetation) and in the ocean. Units: gigatonnes (1 Gt = 1 billion tonnes).

Conclusions

The results of this study on possible climate changes for the 21st century can be summarized in the following conclusions:

The future global warming is directly dependent on the chosen emission scenario. By the end of the 21st century, it reaches 2.5°C in scenario B1, 3.7°C in scenario A1B and 4.1°C in scenario A2 relative to the mean value of the years 1961 to 1990. In the last report of the IPCC, large uncertainties from 1.4 °C to 5.8 °C were documented, resulting primarily from the greater range of the assumed scenarios.

- The land surface warms more than the ocean. In particular, warming in the Arctic is up to three times greater than the global average.

- Worldwide an increase in heat waves is expected. In the second half of this century, heat waves, as seen in the summer of 2003, will become commonplace in Europe.

- As a result of warming, the global precipitation rate will increase by about 2% per degree of global warming. An increase in the rate of precipitation is expected in the tropics and in the high latitudes, whereas lesser precipitation is expected in the Mediterranean region, South Africa and Australia - amongst others. The change in the rate of precipitation in Europe and other areas, (e.g. South America and Central Africa) is closely related to the seasonal shifting of the climate zones. In the Mediterranean region a distinctive decrease in precipitation is simulated for winter. In summer this anomaly will shift northwards, whereby areas of Southern and Central Europe will experience a decrease in precipitation. In Central Europe, in particular Scandinavia, the precipitation will increase in winter. Precipitation in winter will fall predominantly as rain. By the end of this century, snowfall in Central Europe will decrease by 80-90%, whereas in the high altitudes of the Alps and in the Norwegian mountains a decrease of 30-50% is expected.

- Heavy precipitation and the resulting risk of flooding will increase globally. The duration of dry periods will also increase globally, apart from the high latitudes (e.g. Alaska and Siberia). Thus, not only will we see an increase in contrast between relatively humid climate zones (tropics and high latitudes) and relatively dry climate zones (subtropics), but also an increase in the precipitation extremes between the respective regions.

- The warming of the oceans will result in sea-level rise. A global mean sea-level rise of 21 cm in scenario B1 and 28 cm in A2 is expected by 2100 (relative to the mean value between the years of 1961-1990). Regional differences will range from a slight fall in certain areas, to a rise of more than 1 m in others. In addition, a rise in the global sea-level of up to 8 cm (A1B, A2) will result from a change in land-ice volume. This results from a combination of melting in Greenland and increased snow-fall in Antarctica, increasing and reducing the sea-level by 13 and 5 cm, respectively.

- The distinctive warming of the Arctic results in thinner ice in winter and reduced ice area in summer. The shrinking of the summer ice observed in recent years will continue increasingly. By the end of the century, scenarios A1B and A2 predict the Arctic to be ice-free in late summer.

- A decline in surface water density in the North Atlantic, through higher temperatures and an increase in precipitation will result in a weakening of the thermohaline circulation by about 30%, by the end of the 21st century. The resulting reduction of the oceanic heat transport will however not result in regional cooling, but will partially compensate for the warming resulting from the increase in greenhouse gases. This "thermostatic effect" will have no considerable influence on the European climate. Despite less warming in the North Atlantic, warming of the European continent will be insignificantly less than in comparable regions.

- So far, a fraction of the global warming has been masked by the increase in anthropogenic aerosol emissions (sulphur, soot, amongst others). Measures to improve air quality will contribute to additional climate warming because the masking effects of anthropogenic aerosols, due their very short lifetime, will rapidly diminish. Increased efforts to lower greenhouse gas emissions will be the sole compensation for this consequence.

Sources of uncertainty in the climate projections for the 21st century are:

- Future emissions;

- Natural fluctuations which overlie the anthropogenic trends;

- The coarse grid resolution of about 200 km;

- Calculation of processes that are not resolvable within the grid resolution;

- Missing processes, for example the biogeochemical cycles.

The changes in the concentrations of the atmospheric greenhouse gases are determined by the complex interactions between physical, chemical and biological processes in the atmosphere, the ocean and on the land surface. In current climate models, interactions between climate and the carbon cycle, as well as other biogeochemical cycles (methane, ozone, etc.) are generally neglected. However, initial investigations point to a positive feedback between the climate and the carbon cycle. Accordingly, global warming caused by anthropogenic CO_2 emissions reduces the Earth's capacity to store carbon dioxide (in vegetation, soil and ocean sinks) and hence contributes to further warming. Advances in the understanding of the Earth system and the predictability of future climate change will only be realized through an interdisciplinary collaboration within the framework of a broadly defined Earth system research strategy.

A considerable source of uncertainty within the current models results from their insufficiently detailed grid resolutions, limited by current computational capacity. A finer resolved model would allow a better simulation of changes in the statistics of extreme weather events such as flooding, dry spells, heat waves and hurricanes. These changes are of substantial interest, because climate change affects humanity considerably more through extreme events than through changes in the mean climate. Progress in the predictability of extreme events can only be realized through advances in computational capacity.

Climate Research at the Max Planck Institute for Meteorology

The overall mission of the MPI-M is to understand how physical, chemical and biological processes, as well as human behaviour contribute to the dynamics of the Earth system and specifically how they relate to global and regional climate change. The key research tools are the high-end numerical models, which simulate the behaviour of the atmosphere, the ocean, the cryosphere and the biosphere, as well as their respective interactions.

What is a Max Planck Institute?

Max Planck Institutes are concerned with basic research that goes beyond the capabilities of German universities, due to the interdisciplinary nature of the research or high costs for personnel and equipment. Max Planck Institutes are therefore complementary to universities; in some areas their activity is predominant, whereas in others a more supplementary role is provided. Gaining new knowledge at the frontier of science demands a high level of competence and commitment, but also yields the most innovative results. This is the achievement expected of the Max Planck Institutes and is testament to its eminence in Germany and the world. Max Planck Institutes are regarded as national and international "CENTRES OF EXCELLENCE" for basic research.

Organisation: The Max Planck Institute for Meteorology is one of the currently 80 scientific institutes of the Max Planck Society for the Advancement of Science.

Funding: The Max Planck Society for the Advancement of Science is primarily supported by public funds, granted by the German federal government and the individual states. The Max Planck Institute for Meteorology has a total budget of about 7 million Euros; in addition, external funding for research projects is obtained.

Staffing: In the middle of 2005, the institute had a total staff of 196. This consisted of 25 senior scientists, 37 junior scientists, as well as 73 staff members financed by external funds and 2 visiting scientists.

Managing Director: Professor Martin Claussen

Scientific members and Directors:
Professor Martin Claussen, Professor Jochem Marotzke

Climate Projections for the 21st Century

MPI-M
October 2006