

## 3 WATER AND CLIMATE CHANGE

**W**ITHOUT WATER NO CLIMATE AND WITHOUT WATER NO LIFE. THIS IS WHY WATER IN FORM OF PRECIPITATION IS A BASIC CLIMATE ELEMENT. TOGETHER WITH TEMPERATURE IT IS USED TO DESCRIBE AND CLASSIFY THE FUNDAMENTALS OF CLIMATE. MOREOVER, IN THE CONTEXT OF THE CLIMATE SYSTEM AND THE PROCESSES INVOLVED, IN CONNECTION WITH EVAPORATION, RUNOFF, AND STORAGE, PRECIPITATION IS AN IMPORTANT PART OF THE WATER CYCLE. IT IS A BASIC TASK OF INTERDISCIPLINARY CLIMATE RESEARCH TO MONITOR EXACTLY THESE QUANTITIES AND THEIR BEHAVIOUR FOR THE PRESENT AND THE PAST, TO UNDERSTAND IT PHYSICALLY BY MEANS OF PROPER MODELS, AND TO DERIVE FROM THIS UNDERSTANDING RELIABLE PROJECTIONS FOR THE FUTURE. IN ADDITION, ALL PROBLEMS OF THE RELATED ECOLOGICAL AND SOCIO-ECONOMIC CONSEQUENCES, PARTICULARLY THE RISKS, HAVE TO BE ADDRESSED. NO DOUBT, WATER IN SUFFICIENT QUANTITY AND QUALITY IS ABSOLUTELY NECESSARY FOR LIFE: MANKIND, VEGETATION, AND FAUNA. ON THE ONE HAND, CONFLICT POTENTIALS DUE TO WATER STRESS AND DROUGHTS ARE ALREADY ARISING. ON THE OTHER HAND, OUR PLANET IS THREATENED BY FLOODING DUE TO EXTREME PRECIPITATION.

### 3.1 CHANGES IN THE WATER CYCLE

#### 3.1.1 Global water cycle and climate change – Interactions

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***SUMMARY:** Water provides one of the most important links among the subsystems of the climate system because it connects them all. The residence time of water in the different reservoirs varies from days for atmospheric water to thousands of years for the polar ice and the oceans. The atmospheric water cycle connects different water reservoirs and has a high mobility. There is some evidence from paleoclimatic records and modelling studies for the recent global warming that climate change affects the global water budget which is linked to the availability of water, glaciers and ice sheets extent, sea level, and ocean circulation. We argue that the understanding of the involved mechanisms and feedbacks is essential for the prediction of the future water cycle with its large impact for the world population.*

**W**ater occurs in fluid, solid and gaseous form in the ocean, ashore and in the atmosphere. According to current estimates, circa 97% of the total quantity are located in the oceans in the form of salt water. Circa 2% are contained in ice masses covering Greenland and the Antarctic as a result of several thousand years of storing atmospheric precipitation. Further 0.6% are freshwater in groundwater, lakes and rivers. The percentage which remains in the atmosphere in the form of water vapour is by several orders smaller but far from insignificant. There are processes of exchange between the water reservoirs: Evaporation and precipitation connect the fluid and gaseous respective solid reservoirs; water discharge from the continents transports the water through the river systems into the oceans. The atmosphere is the component of the Earth system that has the highest mobility. With its typical daily time scale the atmospheric water cycle provides the linkage to the more slowly reacting reservoirs ocean and ice. The atmospheric hydrological cycle consists of the transport of water vapour and the phase transformation into fluid and solid water particles in the clouds, involving large transformations and transports of energy (see Chapter 1.5).

The hydrological cycle and thus the availability of water are of special importance for nature as a whole including mankind. The water cycle determines the presence of vegetation and deserts. Changes in the hydrolo-

gical cycle directly affect the population. Depending on region and quantity, water is experienced as a threat (e. g. floods) or as a blessing (e. g. precipitation in dry areas).

Complex numerical models of the Earth's climate, which can only be run with the aid of expensive mainframe computer systems, are suitable to examine and understand changes in the hydrological cycle and its interactions in the climate system. A general circulation model of the atmosphere like the ECHAM (developed in Hamburg) describes the climatically relevant processes with their complex interactions in a global, three-dimensional computational grid. Results from this model's assessment of climate and water distribution at present as well as during the ice age will be discussed in the following paragraphs. To estimate future climate evolution, coupled circulation models for atmosphere and ocean are used. The results from this and other climate models enter the assessment reports of the Intergovernmental Panel on Climate Change (IPCC 2001), the advisory board of the UNO in matters of climate. The water distribution at the end of the 21<sup>st</sup> century predicted with a coupled circulation model is presented in the paragraph on future climate development. That paragraph also deals with possible impacts of the greenhouse climate on the ice covering Greenland and the Antarctic. You will find an outlook in the last paragraph of this contribution.

## Today's water distribution

Today's water distribution on the Earth's surface is mainly determined by the atmosphere's large-scale circulation, which effectuates how much freshwater evaporates from the ocean, where the water vapour condenses into clouds, and how much of it rains onto the continents. *Fig. 3.1.1-1* shows the world-wide distribution of net precipitation (precipitation minus evaporation) for the present climate, calculated by means of the ECHAM circulation model of the atmosphere. This distribution reflects the atmospheric circulation: In the innertropical convergence zone an intensive ascension of air warmed by strong solar radiation (convection) causes strong precipitation. In the subtropics, where high air pressure and thus sinking, dry air masses prevail, evaporation predominates. Evaporation is strongest in the subtropical areas of the ocean, which are therefore the most important sources of atmospheric water vapour (see Chapter 1.5). Due to the loss of evaporated water, the sea water there has a relatively high salt content at the surface, while the Earth's large deserts (Sahara, Gobi, Australian desert, etc.) spread across the subtropical continents, because there the already low precipitation evaporates again. In higher latitudes, precipitation predominates evaporation; towards the poles, however, its quantity diminishes fast with decreasing temperature, since cold air masses can absorb considerably less water vapour than warm ones.

On the basis of precipitation, evaporation, and temperature the distribution of ice on Earth can be explained. The prevailing precipitation in the polar regions is snow. When it does not melt completely in summer, this may cause the development of ice sheets resp. balance a loss of ice by melting and calving of icebergs. The two largest ice sheets of the Earth with a volume of 25.71 resp. 2.85 million km<sup>3</sup> are situated in the Antarctic resp. Greenland. Their melting would raise the sea level by 61.1 m resp. 7.2 m. Compared with this, the volume of all other glaciers of the Earth does only encompass 0,18 million km<sup>3</sup>, corresponding to a sea-level rise by 0.51 m (*Table 3.1.1-1*).

## The water cycle during the last ice age

The water cycle and the distribution of water changed considerably during the Earth's history. On very long time scales the water cycle even determines the varying distribution of inland ice sheets. During the last circa 2 million years (Quaternary) there were several changes between ice ages and warm times with significant changes in the global distribution of water, which is documented by lots of indirect information, so-called proxy data from climate archives (CROWLEY & NORTH 1990). Inland ice is a slowly changing climate component which on the one hand

depends on the climate and on the other hand retroacts on it, e. g., because its surface reflects the sunlight. As the quantity of water in the Earth's system is constant, the water quantity bound in inland ice sheets and glaciers determines the global sea level, because the atmosphere, the river systems, lakes, and soils are relatively insignificant for global water storage. During the Last Glacial Maximum (LGM) circa 20,000 years ago so much water was bound in the form of ice in the inland ice sheets of the northern hemisphere that the sea level was by 120 m lower than today. Bering Strait, e. g., between Siberia and Alaska then was a land passage used by prehistoric men to immigrate to America (PELTIER 1998). *Table 3.1.1-2* shows the proportions of the different ice sheets regarding additional water storage during the last ice age in the form of a change in sea level.

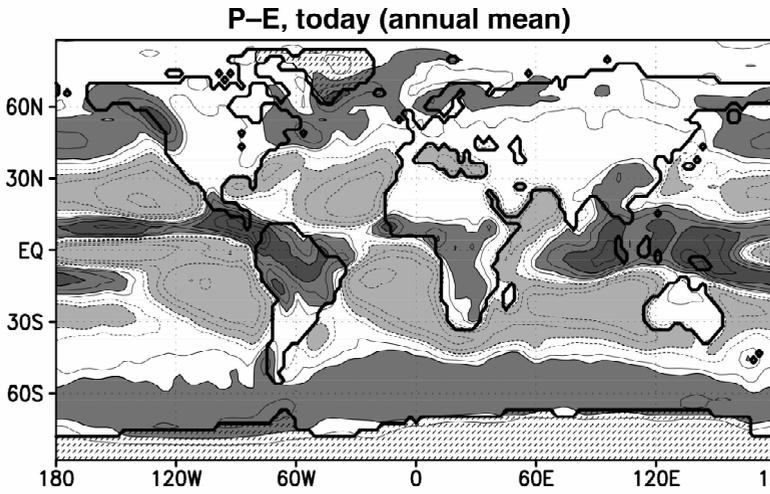
*Fig. 3.1.1-2* shows the change in net precipitation at the LGM 21,000 years ago, compared to today, calculated by means of the circulation model ECHAM. The large inland ice sheets are recognisable (the Laurentian ice sheet across North America, the Fennoscandian ice sheet across Northern Europe as well as smaller ice sheets across Siberia and South America), and we can also discern the altered distribution of land and sea, caused by the lower sea level. Especially on the ice sheets and in their surroundings, the temperatures are by more than 20 °C lower than today. The temperatures of air and water in the tropics during the last ice age, however, were only slightly lower than now. The quantification of this cooling still poses methodical problems for scientists trying to reconstruct relevant climate information from proxy data (Mix et al. 2001). Nevertheless, it is relatively clear that in a global mean it was by circa 4 °C colder at that time than it is today. Due to this cooling the net precipitation is mostly smaller (compare

**Table 3.1.1-1:** Ice sheets and glaciers: surface, volume and equivalent sea-level rise in case of melting (according to IPCC 2001, Table 11.3).

	<i>Antarctic ice sheet</i>	<i>Greenland ice sheet</i>	<i>Remaining glaciers</i>
Area (10 <sup>6</sup> km <sup>2</sup> )	12.37	1.71	0.67
Volume (10 <sup>6</sup> km <sup>3</sup> )	25.71	2.85	0.18
Sea level (m)	61.1	7.2	0.51

**Table 3.1.1-2:** Sea-level difference (lowering compared to today's values) in metres due to the additional storage of water in the ice sheets during the LGM 21,000 years ago (according to PELTIER 1998).

<i>Sea-level difference (m)</i>	
North America	60.4
Eurasia	29.8
Antarctic	21.7
Greenland	5.8
<b>Sum</b>	<b>117.8</b>



**Fig. 3.1.1-1:** Net precipitation (precipitation P minus evaporation E in millimetres per day) on a long-time average, calculated by means of the circulation model of the atmosphere ECHAM 3. The continents' outlines are recognizable in the model's resolution, Greenlandic and Antarctic ice shields are crosshatched. Areas predominated by precipitation are marked by solid lines (0.5, 1, 2, 3, 5, 7, 9 mm per day) and dark shades (3 and 1 mm per day); areas predominated by evaporation are marked by dotted lines (-0.5, -1, -2, -3, -5 mm per day) and a light shade (-1 mm per day).

dotted lines in Fig. 3.1.1-2). This can also be observed in higher latitudes on and around the ice sheets as well as in several tropical areas with much precipitation. In parts of the tropical Indian and Pacific Ocean the areas where evaporation prevailed were smaller during the LGM.

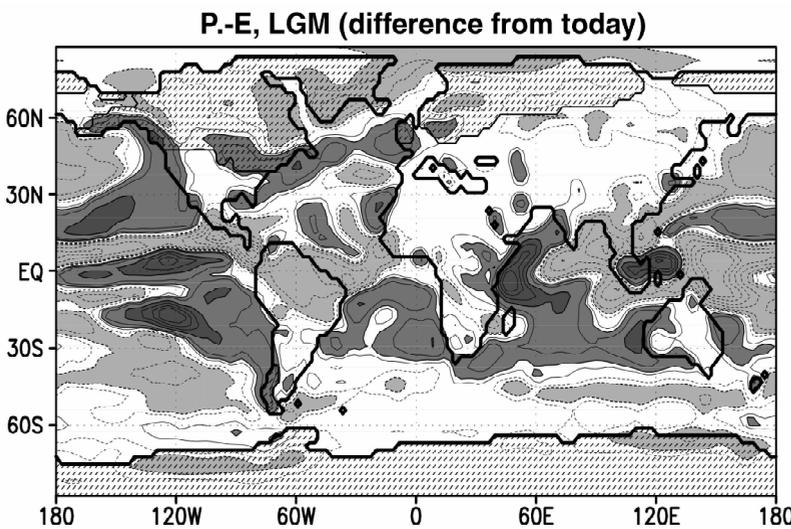
A comparison between the present conditions and those of the last ice age shows a considerable, climate-related displacement of water distribution. During the LGM the ice volume was by 50 million km<sup>3</sup> larger than today. Between circa 20,000 and 7,000 years ago the inland ice sheets melted back to today's total volume with very different melting rates during the various melting phases and an equivalent sea-level rise of sometimes more than 15 metres per 1,000 years. We assume that the most important reasons for this momentous process are, among others, changes in the parameters of the Earth's orbit as well as in the carbon

cycle, their direct impact being intensified by different feedback processes in the climate system.

**The future of global water distribution**

How much water in its liquid and solid form will there be in the future? Do we have to expect serious cooling due to a new ice age or will the release of greenhouse gases by fossil fuel burning cause global warming? In order to find answers to these questions we have to separate between natural climate changes on the one hand and those caused by man on the other.

For the natural climate evolution during the Quaternary the orbital parameters of the Earth are of great importance. As early as at the beginning of the 20<sup>th</sup> century the Serbian mathematician MILUTIN MILANKOVITCH (1941) calculated their impact on the seasonal distribution of solar radiation



**Fig. 3.1.1-2:** Change in net precipitation (annual mean of precipitation P minus evaporation E in millimetres per day) during the Last Glacial Maximum (LGM, 21,000 years ago) compared to today's climate, calculated by means of the circulation model of the atmosphere ECHAM 3 (LOHMANN & LORENZ 2000). The ice sheets during the LGM are crosshatched; the altered distribution of land and sea is recognizable. Areas that were more humid than they are now (Fig. 3.1.1-1) are marked by solid lines (0.25, 0.5, 1, 2, etc. mm per day) and darker shades (2 and 0.5 mm per day); drier areas are marked by dotted lines (-0.25, -0.5, -1, -2, etc. mm per day) and a light shade (-0.5 mm per day).

at the Earth's surface. For a long time his thoughts have been discussed as the astronomical theory of the ice ages. Variations in the seasonal distribution of incoming solar radiation (insolation) of more than 100 Watt per square metre during the Quaternary caused significant influence on climate. The orbitally-induced insolation forcing possibly triggered the occurrence and disappearance of continental ice shields and acted as a pacemaker of ice ages during the late Quaternary (HAYS et al. 1976). Similarly, the changing insolation is of importance for the climate changes of the last 10,000 years (the Holocene). Data and climate modelling synthesis suggests that a large part of different regional climate trends from the mid-Holocene warm period (7,000 years ago) until now are caused by the orbital insolation forcing (LORENZ et al. 2006).

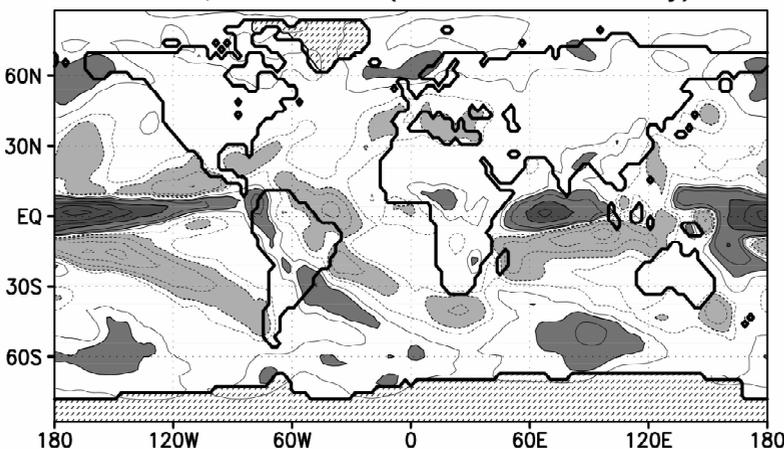
New studies which examine the long-term, natural climate development and excluding the anthropogenic greenhouse effect predict a long warm period on account of relatively small changes in the Earth's orbit; only after 50,000 years another glacial period could be expected (BERGER & LOUTRE 2002). In addition, the atmospheric composition, in particular the anthropogenic increase of greenhouse gas concentration, will have a much greater impact on our climate than the variability of solar radiation caused by changes of the orbital parameters. Apart from water vapour, carbon dioxide is the most important radiatively active gas in the atmosphere and thus takes great influence on temperatures. Its proportion in the atmosphere has increased from 280 ppm (parts per million) to currently 370 ppm since the beginning of industrialisation on account of fossil fuel burning. By contrast, this concentration has never exceeded the limit of 300 ppm during the last 420,000 years, probably not even the last 20 million years (IPCC 2001, 3.3.01). According to the IPCC scenarios it will be between 550 and 950 ppm at the end of the 21<sup>st</sup> century.

This man-made increase is highly responsible for the global warming of 0.6 °C over the last one hundred years and could cause a further warming of 1.4 to 5.8 °C within the next 100 years (IPCC 2001). During the last million years changes in temperature to this extent have also been triggered by changes of the orbital parameters of the Earth, but within much longer time scales of thousands of years.

These climate changes will necessarily also affect the atmospheric water content and – if the temperature rises further – the global distribution of water after the year 2100. Provided that the mean temperature will rise by 2.3 °C till the middle of the 21<sup>st</sup> century evaporation and precipitation will increase by 5.2 per cent, i.e. in the global mean from 900 to 950mm per year, according to model simulations (WETHERALD & MANABE 2002). Evaporation will increase rather at low than at high latitudes, precipitation on the other hand rather at the equator and at high latitudes. These tendencies are shown very differently at regional levels by various model simulations. However, on a global scale the calculations on precipitation taken into account by the IPCC show great correspondences (IPCC 2001, 9.3.2). The ECHAM model also shows a rise of the net precipitation by 1mm per day at the polar-regions and an extremely high increase (5 mm per day) in the equatorial Pacific and Indian Oceans (Fig. 3.1.1-3). On the other hand, evaporation will be stronger from the subtropics to the Mediterranean region. Based on ensemble simulations WETHERALD & MANABE (2002) come to similar results.

Looking at the development from the last ice age to the near future we will find the influence of the temperature on the water cycle confirmed: evaporation and precipitation increase at rising temperatures (Fig. 3.1.1-2 and 3.1.1-3). The changes in temperature and the water cycle are closely correlated. As temperatures in higher regions are expected to rise to an extremely great extent, precipitation will fall

**P–E, scenario A2 (difference from today)**

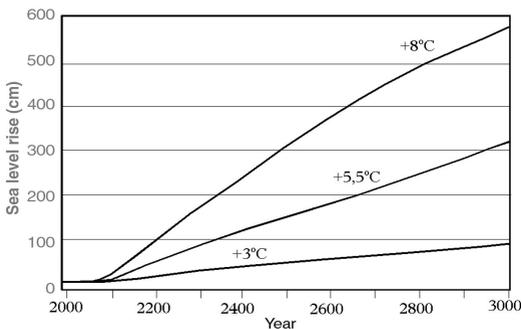


**Fig. 3.1.1-3:** Change in net precipitation (annual mean of precipitation P minus evaporation E in millimetres per day) at the year 2085 in a climate scenario simulation (scenario A2, IPCC, Box 9.1) compared to today's climate (mean of the years 1961–1990), calculated by means of the coupled atmosphere-ocean circulation model ECHAM 4/OPYC (STENDEL et al. 2004). Lines and shades as in Fig. 3.1.1-2.

as rain rather than snow. This will cause positive feedback processes: the shrinking of the snow covering and the prolongation of the yearly thawing period will make the temperature rise even further.

While there has been a shrinking of the snow covering and the Arctic sea ice in the northern hemisphere during the last decades, the effect of the global temperature rise on the ice sheets of Greenland and Antarctica for now and the next hundred years cannot be clearly predicted. The question if the ice sheet of Greenland has increased or decreased during the last decades is highly disputed (CHYLEK et al. 2004). For the 21<sup>st</sup> century only a slight shrink of the ice mass is predicted causing a rise of the sea level by 6 cm until the end of this century (IPCC 2001, 11.5.1.1). On the other hand, recent research has shown that thinning, removal, or marginal weakening of the ice shelf in front of outlet glaciers, like the Jakobshavn Isbrae on the west coast of Greenland, will speed the flow of inland ice with important consequences even on decadal timescales (ALLEY et al. 2005).

In the coming centuries the ice sheet of Greenland will probably react quite differently to global warming (Fig. 3.1.1-4). A longer period of average yearly global warming by 3 °C above the present level will be – according to model simulations – the point at which the ice sheet will lose more of its mass by the thawing process than it will gain by snowfall. If the temperature rose by 8 °C, the ice sheet would melt completely by the next 1,500 years. However, in the long run, even a temperature rise of only 3 °C over a period of 1,000 years or longer would cause the total thawing of the Greenland ice sheet (GREGORY et al. 2004). In this case there would be a redistribution of the global water resources from their firm to their liquid form which would result in a sea level rise of about 7 metres. Even after a possible return of the global climate to conditions before industrialisation the loss of the Greenland ice sheet would be irreversible. Without the ice sheet the climate of



**Fig. 3.1.1-4:** Reactions of the Greenland ice sheet to global warming according to three climate scenarios during the third millennium in cm of sea level rise. The model calculations assume a rise of the greenhouse gas concentration until 2130 and stabilisation afterwards (after to IPCC 2001, Fig. 11.16).

Greenland would change drastically and stay much warmer than today – due to a lower surface as well as the decrease of sun reflection (GREGORY et al. 2004).

Differently from Greenland, there is no significant surface ablation in Antarctica with temperatures below zero even in the summer period – with the exception of some coastal regions of West Antarctica and the Antarctic Peninsula. The Antarctic ice sheet loses mass mainly by iceberg calving at the seaward edges of ice shelves.

The Antarctic ice sheet will probably react by a positive mass balance to a future global warming, because a world-wide rise of temperature will intensify the water cycle so that more snow will fall on Antarctica (Fig. 3.1.1-3). Like in Greenland, ice-flow acceleration of glaciers along the Antarctic Peninsula, caused by the disintegration of ice shelves like the Larsen B ice shelf, have been observed too (KERR 2006). The main cause is not a higher temperature of the atmosphere, but ocean warming. A collapse of the unstable West Antarctic Ice Sheet could thus be a potential response to global warming. In all likelihood this will not happen during the 21<sup>st</sup> century. But over a period of several hundred years a continued warming of the atmosphere and the adjacent oceans can cause a complete disintegration of the West Antarctic Ice Sheet. This would cause a global sea level rise of about 4 to 6 metres.

### Final remarks

A changed relation between precipitation and evaporation could have significant consequences for some regions already in the 21<sup>st</sup> century. Thus there will be likely an expansion of subtropical dry zones in the Mediterranean area. On the other hand more precipitation is expected at high latitudes. Generally there will be more extreme rainfalls bearing the danger of droughts or floods (compare Chapter 3.1.11). A greater redistribution of the global water resources from its solid to its liquid form over a longer period of time cannot be without consequences for life on Earth and will also influence the climate. A rise of the sea level by several metres, as it seems possible during the following centuries due to the melting of parts of the ice sheets in Greenland and Western Antarctica, could cause the disappearance of small island states in the Pacific and Indian Ocean and the flooding of densely populated low lying coastal areas around the world. Furthermore the melting of the Greenland ice would increase the amount of freshwater input into the North Atlantic. This could weaken the so-called thermohaline circulation in the Atlantic. This deep ocean circulation is responsible for the transport of warm water from the Gulf of Mexico up to the northern North Atlantic and produces relatively warm temperatures in North-west Europe. A weakening or even shut down of the deep circulation in the North Atlantic may cause a considerably cooler climate in North-west Europe ♦