The climate is changing – but why?

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1. Introduction

The mean temperature at the Earth's surface is increasing, and at the same time the patterns of precipitation are changing towards more intense rainfall and longer periods of drought. These changes are controlled by physical as well as biological processes. Even though there are natural processes which can lead to global temperature increases, research shows that human (anthropogenic) activities – especially CO_2 emissions – are most likely to be the main reason for the increasing temperatures on Earth over the past 30 years. Model calculations show that global temperatures will probably increase by 1.8-4.0 °C during the twenty-first century depending on emissions of greenhouse gases.

Following the Fourth Assessment Report (AR4) of the UN's Intergovernmental Panel on Climate Change (IPCC) and Al Gore's documentary 'An Inconvenient Truth' as well as the Nobel Peace Prize which was awarded to the IPCC and Al Gore in 2007, there has been an unparalleled level of attention on man-made climate change. This is largely due to the fact that the IPCC now concludes that: "Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations." However, in the media this is still being debated although most researchers support this conclusion.

IPCC – the UN's climate panel **Box 1**

The UN's climate panel is called the IPCC, which stands for 'Intergovernmental Panel on Climate Change'. It was set up in 1988 as a follow-up to the Brundtland Report – 'Our Common Future'. Based on its reviews of scientific literature, about every five years the panel publishes a summary and an assessment of research and knowledge on climate change and the effects of these changes. The scientific reviews are conducted by recognised scientists within the various fields. The scientists are appointed by the UN's member countries. The assessment consists of a report from each of the three main working groups:

- Working group I: Describes the scientific aspects of the climate system and climate changes.
- Working group II: Describes vulnerabilities in the socio-economic and natural systems in the face of climate change, impacts as well as the possibilities for adaptation.
- Working group III: Describes how to reduce emissions of greenhouse gases and other ways of preventing climate change.

In addition to these assessment reports, the IPCC also publishes a number of special reports on specific subjects, for example emission scenarios, technologies for reducing emissions or methods for calculating greenhouse gas emissions. The latest assessment report (the fourth) was published in 2007. The IPCC does not conduct independent research itself on climate changes or their impacts, but is charged with drawing conclusions from the available scientific literature on the subject.

2. Climate changes – what's happening?

Worldwide, the temperature has increased by 0.7-0.8 °C since the end of the nineteenth century. By far the largest share of this increase (0.55 °C) has occurred within the past 30 years. However, it is not just the temperature which has increased. Other aspects of the climate systems have also changed:

- Sea levels worldwide have risen, and the rate of increase is growing, such that sea levels are now rising by 3-4 mm per year.
- In many places, ice caps and glaciers are melting, contributing to rising sea levels.
- Snow cover in the northern hemisphere has decreased by about 5 per cent since 1966.
- The area covered by permafrost has decreased by 10 per cent in the northern hemisphere.
- The extent of Arctic sea ice has decreased by 20 per cent since 1978.

- Precipitation has increased at high latitudes in both the northern and southern hemispheres.
- There are more periods of drought. This increase in droughts has mostly been observed in the already dry areas of the world, i.e. the dry tropics and subtropics.
- The frequency of heavy precipitation has increased, even in areas with reductions in total rainfall.
- There is no change in the number of tropical hurricanes, but they tend to be stronger and to last longer.

Over a longer time-scale, climate on Earth has varied considerably more than what we have seen in recent decades. However, we only have reliable measurements of temperature and precipitation for the past 150 years or so. To look at the climate over longer periods of time, we must resort to indirect measurements. Here, measurements of e.g. oxygen isotopes in ice cores and sediment layers play an important role in describing the climate (Box 2). However, there are considerable uncertainties associated with translating these observations into a global average temperature. Using such measurements, the IPCC assesses that the global average temperature during the past 50 years has not been as high for the past 1,300 years.

3. The Earth's radiation balance

As mentioned above, in the course of the Earth's long history the climate has varied considerably more than what has been observed within the past 100 years. Basically, the climate is determined by the balance between the energy which is supplied by sunlight, and the energy which is lost through longwave heat radiation from Earth (Figure 1). Two factors in particular affect the radiation balance: 1) The amount of sunlight intercepted by Earth, and 2) the strength of the greenhouse effect.

Incoming solar radiation corresponds to an average of about 342 W/m^2 on the entire Earth's surface, day and night, 365 days a year. However, 31 per cent of this radiation is reflected by clouds, atmospheric particles and the Earth's surface. This is called the planetary albedo. It is the remaining 69 per cent (or 236 W/m^2) which heats the Earth and the atmosphere.

Earth loses heat by emitting longwave infrared radiation. The amount of longwave radiation is proportional to the absolute temperature to the fourth power (Stefan-Boltzman's law). Over a long period of time, the outgoing radiation will be the same as the incoming radiation (236 W/m^2). Using Stefan-Boltzman's law, this gives a mean temperature for the globe

Measuring temperature

Box 2

Traditionally, air temperature is measured by placing a thermometer in what is termed a Stevenson screen, which provides shade and ventilation, ensuring that it is the air temperature that is measured and not the effect of solar radiation on the thermometer. Such measurements have been conducted worldwide since the mid-nineteenth century. Temperature measurements are affected locally by urban development (the urbanisation effect), and it is being discussed whether such effects have affected the global temperature series so they show excessive temperature increases. It is well known that the climate in large cities is significantly warmer than beyond the city limits, but by far the most weather stations are situated in the countryside, far away from urbanised areas. Moreover, temperature measurements from towns and cities are corrected to take account of the urbanisation effect. A number of recent studies show that, at most, urbanisation produces a small uncertainty (0.06 °C over 100 years), which is far less than the observed increases in temperature.

In recent decades, measurements using satellites have provided new ways of measuring the Earth's temperature. However, such measurements provide information in particular about changes in temperature distribution at various heights in the atmosphere. Here, observations show that the temperature in the uppermost part of the atmosphere has been falling, which ties in with the greater greenhouse effect leading to reduced outgoing radiation from the lowest part of the atmosphere. Reconstructing the temperature over longer time-scales calls for other – indirect – methods. Geological deposits provide information about the fauna and flora in the past, and the composition of these organisms provides information about climatic and temperature conditions at the time when these organisms were living. Similar information can be obtained by studying the thickness of tree rings.

Studies of longer time-scales are concentrated on ice cores in Greenland and on the Antarctic as it is possible to indirectly read the variations in temperature several hundred thousand years ago. One of the most important methods of reconstructing the temperature back in time is to measure the amount of different forms of oxygen (oxygen isotopes), both the ordinary oxygen isotope ^{16}O and the heavier and rarer ^{18}O. Oxygen is the heaviest constituent of a water molecule (H_2O), and as it is easier for the lighter ^{16}O to evaporate than the heavier ^{18}O, in colder periods there will be less ^{18}O present in the atmosphere than in warmer periods. The relative content of the two isotopes in the ice caps can therefore tell us about the temperature of the atmosphere at the time when the snow fell. In cold periods there will be less ^{18}O present in the atmosphere than in warmer periods. The relative content of the two isotopes in the ice caps therefore tell us about the atmosphere's temperature at the time when the snow fell.

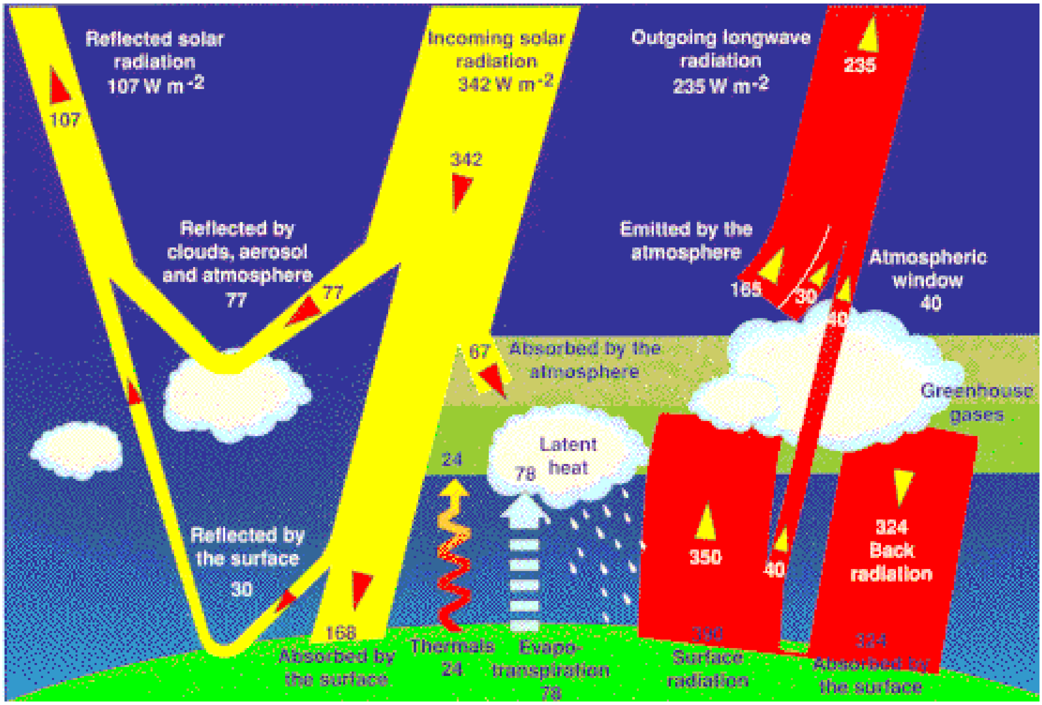


Figure 1: The Earth's radiation balance consists of the balance between incoming solar radiation (shortwave radiation) and solar radiation reflected by clouds and the surface of the sea and the Earth as well as longwave heat radiation from the surface, sea, clouds and atmosphere (Taken with permission from H Meltofte (ed.) (2008): Klimaændringerne: Menneskehedens hidtil største udfordring. The Environmetal Library. Hovedland Publishers)

of 254 °Kelvin (approx. -19 °C). This is about 34 °C lower than the mean temperature of 15 °C which has been measured. Another mechanism (the greenhouse effect) must therefore be influencing climate on Earth.

A number of gases in the atmosphere (for example water vapour, carbon dioxide and methane) are, like the clouds, able to absorb some of the outgoing longwave infrared radiation. The absorbed radiation warms the air and is emitted again as longwave radiation, just at a lower temperature than at the Earth's surface as the atmospheric temperature declines with height. Seen from space, the heat is not emitted from the Earth's surface but from greenhouse gases and clouds some way up in the atmosphere. On average, it is at the level where the effective outgoing radiation temperature is 254 °Kelvin (at a height of just over 5 km).

With a greater concentration of greenhouse gases in the atmosphere, the radiation effectively takes place higher up in the atmosphere and for a period at a lower temperature, so that heat builds up in the climatic system until

Box 3: Feedback mechanisms

The Earth's climate system consists of a closely interconnected system involving the atmosphere, land, ice, soil and vegetation. If the temperature changes, it will lead to changes in the other components, which in turn may affect the temperature. These feedback mechanisms can both enhance and weaken temperature changes. Here are a few examples of feedback mechanisms:

Water vapour

Water vapour is a greenhouse gas, but the maximum amount of water vapour that the atmosphere can contain greatly depends on temperature (almost 7 per cent increase for every 1 °C increase in temperature). The warmer it is, the more water vapour the atmosphere can hold, and the greater the warming effect from the water vapour (positive feedback).

Snow and ice

Warming leads to a melting of snow and ice on the Earth's surface and consequently a reduction in snow cover and sea ice. This minimises the amount of reflected sunlight to space and leads to additional warming (positive feedback). This is the main reason why global warming leads to the greatest temperature increases at high latitudes.

Clouds

Clouds affect the climate system in varying ways depending on how high they are in the atmosphere. This is because clouds have an insulating effect while also reflecting sunlight. High clouds generally have a warming effect while low clouds are cooling. The overall effect of clouds is thought to be cooling, corresponding to about 20 W/m^2. This should be seen in relation to the fact that man-made changes in the radiation balance so far are only approximately 1.6 W/m^2 (Table 2).

CO_2

Man-made climate changes are particularly due to emissions of CO_2 from using fossil energy and from deforestation. Over longer periods of time, however, CO_2 also plays a role in feedback systems. For example, the solubility of CO_2 in sea water falls with increasing temperature, which reinforces the role of CO_2 as a greenhouse gas. Warming also increases the temperature in areas with permafrost where very large quantities of carbon are fixed in the soil, which is released at higher temperatures. This too amounts to a positive feedback.

Temperature profile in the atmosphere

The temperature change will be greater at the effective level of outgoing radiation higher up the atmosphere than at the Earth's surface. On the surface there will therefore be smaller temperature changes (negative feedback).

Heat transport

Large volumes of energy are transported in the atmosphere and in the oceans. In a changed climate, these flow patterns can become altered, which can lead to both positive and negative feedback.

Vegetation

The Earth's vegetation influences how much sunlight is reflected and how much water evaporates. As vegetation is also influenced by changes in temperature and precipitation, there is the possibility of many different feedbacks which can be very hard to predict.

the Earth's temperature again corresponds to the loss through outgoing heat radiation. This leads to warming in the lowest part of the atmosphere.

4. Greenhouse gases

The most important greenhouse gases are water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), CFC (chlorofluorocarbons) and tropospheric ozone (O_3) (Table 1). It is not possible to rank with any certainty the effect of the individual gases with respect to the total greenhouse effect. This is, among other things, due to a number of feedback mechanisms between the greenhouse gases (Box 3). Basically, the ratio between the most important greenhouse gases – water vapour, clouds and carbon dioxide – is estimated at 2-1-1.

Table 1. Estimates of the radiation contributed by a number of factors which influence the overall radiation effect of the greenhouse gases (W/m2) for 2005 compared with pre-industrial levels (Solomon et al. 2007).

Cause	Type	Factor	Radiation effect (W/m^2)	
Man-made	Long-lived greenhouse gases	Carbon dioxide (CO_2)	1.66	(1.49-1.83)
		Methane (CH_4)	0.48	(0.43-0.53)
		Nitrous oxide (N_2O)	0.16	(0.14-0.18)
		CFC	0.34	(0.31-0.37)
	Ozone	Stratospheric	-0.05	(-0.15-0.05)
		Tropospheric	0.35	(0.25-0.65)
	Stratospheric water from CH_4		0.07	(0.02-0.12)
	Surface albedo	Land use	-0.20	(-0.4-0.0)
		Black dust on snow	0.10	(0.0-0.2)
	Aerosols (particles)	Direct effect	-0.50	(-0.9- -0.1)
		Cloud albedo	-0.70	(-1.8- -0.3)
	Contrails (vapour trails from aircraft)		0.01	(0.003-0.03)
Natural	Solar radiation	Direct	0.12	(0.06-0.30)
Total man-made			1.60	(0.6-2.4)

The man-made sources of CO_2 are the burning of fossil fuels (coal, oil and natural gas) as well as changes in land use, particularly deforestation. Emissions of CO_2 have increased greatly since 1960 (see Figure 2), and the atmospheric content of CO_2 now exceeds by far the natural level seen over the past 650,000 years (140 to 300 ppm). The concentration of methane and nitrous oxide has also increased sharply during the past 50 years. Methane is produced anaerobically, i.e. through the transformation of organic matter under oxygen-free conditions, for example in the rumens of ruminant animals, from livestock waste, landfills and in paddy rice fields. Methane has a global warming potential which is 23 times greater than for CO_2. The methane content of the atmosphere has, compared to pre-industrial levels, risen by 160 per cent, which is largely due to rapidly increasing numbers of livestock and growing volumes of waste.

Nitrous oxide is an even more potent greenhouse gas than methane with a global warming potential which is 298 times greater than for CO_2. The concentration in the atmosphere has increased by 17 per cent compared to pre-industrial levels; it is also a very long-lasting greenhouse gas with a lifetime in the atmosphere of 120 years. Nitrous oxide stems in particular from the microbial transformation of nitrogen in the soil, and the rapidly growing volumes of nitrogen which are added through agricultural activities are the main cause of increased emissions of nitrous oxide to the atmosphere. Emissions of CFC gases from refrigerators, freezers, air-conditioning systems, fire-extinguishing agents etc. also contribute to the greenhouse effect, which is being further intensified by ozone in the lower part of the atmosphere – the troposphere. Ozone is formed when sunlight decomposes mono-nitrogen oxides (NO_x) and carbon monoxide (CO), for example from car and truck exhaust gases. Thus, a large number of different sources of pollution contribute to boosting the atmospheric content of greenhouse gases.

The combustion of coal and oil in particular also results in the emission of many small particles to the atmosphere, which generally have a cooling effect, because they increase the amount of sunlight which is reflected (the albedo). Changes in land use have also increased the albedo, but there is considerable uncertainty regarding both these effects (See Table 1). In addition to man-made factors influencing radiation, there have been very large but relatively brief cooling contributions in connection with volcanic eruptions when many small particles are emitted, increasing the albedo. Finally, variations in solar radiation have also resulted in a slight increase in radiation effects in the first half of the twentieth century (Table 1). A handful of scientists claim that these factors together with other natural causes can be the main reasons for the observed climate changes rather than the emission of greenhouse gases (see subsequent chapter on the sun's indirect influence on the climate).

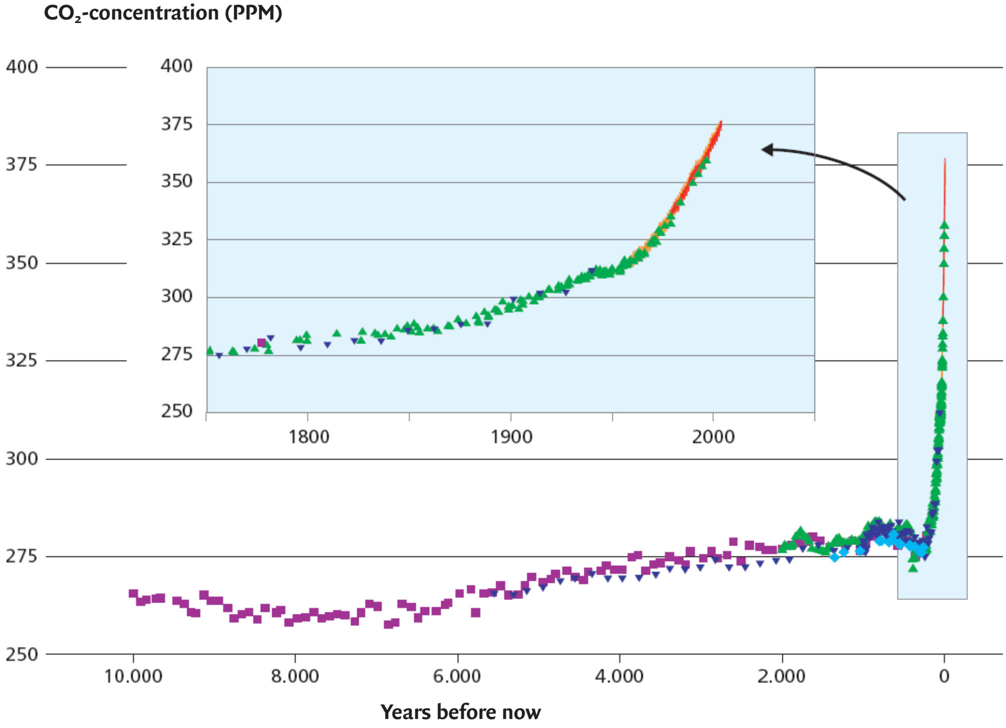


Figure 2. Development in the atmospheric concentration of carbon dioxide (CO_2) following the end of the last ice age measured in air bubbles trapped in ice cores taken from Antarctic ice. The enlarged section shows the concentration for the period 1750-2005. The full-draw line shows direct measurements in the atmosphere (Solomon et al. 2007).

5. Climate sensitivity

Warming as a result of an increase in the atmospheric content of greenhouse gases (or of the other parameters in Table 1) is described using the concept of climate sensitivity. Climate sensitivity states how much the global temperature will rise through a change in additional energy of 1 W/m^2. Such a change in added energy can be due to an increase in the atmospheric content of greenhouse gases or a change in solar radiation.

The climate sensitivity makes it possible to calculate the temperature increase from different forcings of the climate system which, directly or indirectly, influence the energy addition. If we know the change in energy addition, it is then possible, using climate sensitivity, to immediately estimate the temperature change. Unfortunately, we do not know a lot about climate sensitivity. If, for example, we only look at what a change in energy addition should result in based on how dependent the longwave outgoing radiation is on temperature, we arrive at a sensitivity of 0.269 $K/(W/m^2)$.

This produces far too small a climate sensitivity. In reality, a number of feedback mechanisms reinforce the temperature change (Box 3). One of the most important feedback mechanisms is the effect of temperature on the atmospheric content of water vapour. Water vapour is a greenhouse gas, and as a warm atmosphere can contain more water vapour than a cold atmosphere, warming will lead to an enhanced greenhouse effect due to the presence of more water vapour in the atmosphere.

There are many of these feedback mechanisms, and the climate sensitivity is influenced by the combined effect of these. To calculate the overall effect, comprehensive climate models are used which represent all the physical processes in the atmosphere, the oceans and on land. At the same time, observations over the past 150 years have been used, as well as reconstructions of climate changes over the past 500,000 years, to determine the climate sensitivity. Using these methods, a value of approx. 0.75 K/(W/m^2) has been arrived at. Feedback mechanisms therefore result in almost a tripling of the sensitivity compared to the effect without feedbacks. This means that the warming effect of CO_2 will be tripled due to feedback mechanisms in the climate system. However, there is still considerable uncertainty associated with establishing the climate sensitivity, and the estimates range from approx. 0.5K/(Wm^2) to more than 2K/(Wm^2).

Table 1 shows an overall estimated radiative forcing of man-made climate changes of approx. 1.6 W/m^2. A climate sensitivity of 0.75 K/(W/m^2) leads to a temperature increase of 1.2 °C. This is considerably more than the stated temperature increase of approx. 0.75 °C, which is due to inertia in the climate system and which leads to the climate changes continuing for a period after the radiative forcing has increased. This inertia is particularly related to the slow warming of the oceans.

6. The sun’s indirect impact on the climate

In addition to the direct effect of solar radiation on the Earth’s climate (solar forcing), two specific indirect effects of the sun’s influence on the climate have attracted attention in the climate debate. The first effect is due to the absorption (warming) from ultraviolet radiation in the stratosphere’s ozone layer, which is in the uppermost part of the atmosphere (at a height of 15-30 km). The amount of UV radiation depends on sunspots, producing greater warming in periods of maximum sunspots. The number of sunspots varies over an eleven-year cycle. Some studies indicate that the warming can be transmitted to the lower part of the atmosphere and lead to changes in the climate system’s circulation patterns.

The second effect has been suggested by Henrik Svensmark, where the variation in solar activity through changes in the amount of cosmic radiation can affect the formation of ions in the atmosphere and thereby affect the formation of the small particles which function as cloud condensation nuclei for ice and water, and thereby affect cloud formation. Because low-lying clouds in particular have a cooling effect, a change in solar activity can thereby perhaps indirectly affect the climate. Laboratory experiments have shown that this type of radiation can promote the formation of cloud condensation nuclei, but it is unknown whether this mechanism will also work in the atmosphere.

However, there is nothing to suggest that either of these two indirect solar effects have been significant for the global warming of the atmosphere over the past 50 years when there has been no change in the volume of cosmic radiation hitting Earth. On the other hand, it is possible that changes in the cosmic radiation and in UV radiation may have been significant for the warming which occurred in the 1910-1940 period.

7. Ice ages

There has for some time been general consensus among scientists that the basic cause of the coming and going of the ice ages is due to changes in the Earth's orbit around the sun (see Box 4). This is called the Milankovitch theory, and states that the ice ages are caused by small, cyclical variations in the Earth's orbit (eccentricity) and axial tilt (obliquity) around the sun. These variations lead to a complex pattern of changes in the amount and distribution of solar radiation reaching the Earth, influencing global energy balances and heat transport and thereby climate.

During the ice ages, large volumes of water are accumulated in glaciers, causing the sea level to fall. The temperature at the Earth's surface is also lower, resulting in less evaporation of water from the oceans, which in turn leads to less precipitation. Moreover, as much of the precipitation falls as snow, the ice ages are often accompanied by marked periods of drought in ice-free areas. This leads to a global climate which is far less favourable for life on Earth than the present climate. During the ice ages, the climate is not constantly cold, but there are often considerable global and regional variations in the temperature which result in the ice sheets advancing and retreating. The cause of these variations is still poorly understood.

Even though there is general agreement that the Milankovitch theory is the predominant cause for initiating ice ages, it appears that more is required to trigger a new ice age. Here, the amounts of dust and greenhouse gases

Milankovitch and the ice ages

Box 4

The shape of the Earth's orbit around the sun is not constant but varies according to the attractive force of the other planets. Moreover, the Earth's axial tilt (obliquity) and its precession (axial rotation) in space also vary. These variations affect the amount of total solar radiation reaching Earth and its distribution, otherwise known as solar forcing. The Serbian geophysicist Milutin Milankovitch (1879-1958) was the first person to calculate (by hand) these effects over the past one million years and thereby demonstrate that these variations are the primary cause of the switch between ice age and interglacial periods.

Eccentricity

The Earth's orbit around the sun changes from being almost circular to slightly elliptical and back again over a period of approx. 100,000 years. This change in eccentricity means that the distance between the Earth and the sun changes, resulting in minor changes in the overall solar radiation reaching the Earth.

Axial tilt

The angle of axis of the Earth's rotation in relation to an axis perpendicular to the Earth's orbit around the sun varies between 21° and 24° over a period of approx. 41,000 years. Changes in the Earth's axial tilt affect the distribution of solar radiation, but not total solar radiation. When the axial tilt is large, the difference between summer and winter at high latitudes will be greater. Cooler summers with a low axial tilt are suspected of encouraging the start of a new ice age.

Precession

The direction of the Earth's axis of rotation in space changes over a period of about 21,000 years. At the moment it is summer in the northern hemisphere when the Earth is closest to the sun. In about 10,500 years, summer will be in the southern hemisphere when the Earth is closest to the sun. This does not affect the total amount of solar radiation reaching Earth but rather the seasonal variation in temperature.

in the atmosphere are likely to play a significant role. The geography of the Earth is another factor. Only when the position of the continents hinders an efficient exchange between cold water at the poles and warm water at the equator will new ice ages occur. This is actually the case with the Earth's present geography, where there is relatively little exchange between water in the Arctic ocean and the other oceans. At the same time, the continents are currently placed so close to the poles that long-lasting ice caps can be formed.

An ice age typically lasts about 100,000 years, while an interglacial period lasts 10,000-15,000 years. We are now in an interglacial period which has lasted 11,700 years. However, this does not mean we are on the threshold of a new ice age. Thus, the IPCC states that it is very unlikely that the Earth will enter a new ice age within the next 30,000 years as a result of natural causes. This is because the next major fall in summer radiation to the northern hemisphere will not happen for 30,000 years (see Box 4).

Climate models

Box 5

Climate models describe the atmosphere as a physical system based on physical laws which can be expressed mathematically. As the oceans are also an important factor for the climate, climate models often include models of the heat transport and heat exchange taking place within the oceans. In the global climate models (GCM), the atmosphere is described using a number of boxes distributed in a spatial network across the entire globe. There are about 200 km between the grid points, with 30-40 vertical layers in the atmospheric models and 20-30 layers in the ocean models.

The most important physical laws used in the climate models are:

- Equations of motion based on Newton's laws
- Mass and energy conservation
- Equation of state for ideal gases
- Radiation equations, which describe how solar and thermal radiation are transmitted and deposited in the atmosphere.

Moreover, the models include a number of empirical relations based on observations. These empirical relations do not necessarily have a reliable theoretical basis but are necessary to describe processes which occur at temporal and spatial scales which are not sufficiently resolved in the models. Such empirical relations often contain a number of parameters which have to be tuned by comparing model simulations with observations. One example of this is cloud formation, which often takes place on a much smaller scale than what is represented in the models.

The empirical relations are necessary, but they also reduce the degree of precision in the model calculations. This can to some extent be remedied by increasing the models' spatial and temporal resolution, but this leads to vastly greater requirements for computer processing power when running the models. Often calculations are therefore performed with an increased resolution for a smaller geographical area with the help of regional climate models (RCM), where a GCM supplies the boundary conditions for the regional model, i.e. temperature, air pressure, water vapour at the edge of the geographical extent of the regional model.

8. Models of the climate system

As described above, the climate is the result of a complex interplay between many different physical, chemical and biological processes which are simultaneously influenced by the geographical distribution of the oceans, land masses, ice caps, lakes and rivers. In order to better understand this complex system, several mathematical models of the climate system have been developed (Box 5). These are complex models which demand some of the world's fastest computers to simulate the Earth's climate.

The most important criterion for assessing whether a climate model is reliable consists of comparing the model simulations of the present climate with observations. The climate models are continually being improved, and at the moment there are about twenty models worldwide which are capable of producing satisfactory simulations of the climate system. The deviations between the calculated and the observed temperature distribution on Earth are in most cases just a few degrees, with the biggest deviations being seen in areas with snow and ice. Generally speaking, the climate models can be regarded as providing a solid basis for calculating future climate change.

9. Scenario calculations of climate changes

An important question when assessing future climate changes is how society will develop over the next century and how this will affect the emission of greenhouse gases to the atmosphere. To assess the uncertainty in this area and the effect of different social developments, including environmental awareness and new environmentally friendly technologies, the IPCC has developed a number of scenarios for the future (Box 6). These scenarios range from sustainable societies based on the widespread use of renewable energy and resources to an even more resource-hungry society than that we know today.

The global increase in temperature up until 2100 is shown in Figure 3 for three of these scenarios. In about 2100, the temperature globally will have increased by 3-4 °C if the world develops as shown in the A2 scenario, but only by 1.3-2.4 °C according to the B1 scenario.

Most of the other scenarios show temperature increases which fall within this interval (see Table 2). It is worth noting that the differences between the scenarios first become really apparent during the second half of the twenty-first century. This is partly due to the fact that it takes a long time to make the very resource-consuming technologies more sustainable and partly because of inertia in the climate system.

The IPCC's emissions scenarios

Box 6

Future population developments and economic and technological developments will cause additional anthropogenic emissions of greenhouse gases and thereby lead to a greater atmospheric concentration and a continued forcing of the greenhouse effect. At the moment it is difficult to predict how the factors which determine emissions will develop because different international trends have an important bearing, including issues such as the development of the global economy versus a regionalisation of the markets as well as potential changes in people's lifestyles. These changes can either lead to less consumption and thereby relatively small greenhouse gas emissions, or greater consumption of energy and resources and thereby higher emissions. Another important factor is the future of the developing countries where high rates of economic growth and energy consumption on a par with that in the industrialised countries can become a major source of greenhouse gas emissions. The climate issue is thus closely integrated with general development issues.

To assess the necessity/effect of possible measures to reduce the emissions of greenhouse gases, it is necessary to make a number of assumptions about the future. As mentioned, such assumptions are subject to considerable uncertainty, and therefore so-called scenarios are presented which describe *possible* future global social and technological developments. In 2000, the IPCC carried out extensive scenario work that shows a number of possible alternative development perspectives which are gathered in four groups labelled A1, A2, B1 and B2.

A1. A future world with very fast economic growth. The world population peaks in the middle of the century, and new and more efficient technologies are quickly introduced. The A1 family comprises three sub-families where fossil fuels are primarily used (A1FI) or non-fossil energy sources (A1T) as well as a mix of all energy types (A1B).

A2. A more heterogeneous world with continued population growth and a slower pace of technological development.
B1. A world which is similar in some respects to A1, but which focuses more on a service and information-based economy as well as sustainable technologies.
B2. A world which still sees population growth, although at slower rates than in A2, as well as slower and more diversified technological developments than in A1 and B1.

Together, the scenarios cover the many combinations of world population growth (approx. 7-15 billion), growth in GDP (approx. 11-26 times), distribution of energy production on fossil and non-fossil energy sources etc. Even though some optimistic scenarios predict a reduction in CO_2, most show an increase in CO_2 concentration from the present level of 370 ppm to – including a level of uncertainty – from under 500 ppm to more than 1000 ppm up until 2100.

Table 2. Model-calculated projections of global warming and rising sea levels during the twenty-first century (Solomon et al. 2007).

	Temperature increase (°C)		Sea level rise (m)
Scenario	Best estimate	Likely interval	Without accelerated increase in melting rate of ice
Constant year 2000 concentration	0.6	0.3-0.9	
B1	1.8	1.1-2.9	0.18-0.38
A1T	2.4	1.4-3.8	0.20-0.45
B2	2.4	1.4-3.8	0.20-0.43
A1B	2.8	1.7-4.4	0.21-0.48
A2	3.4	2.0-5.4	0.23-0.51
A1FI	4.0	2.4-6.4	0.26-0.59

The climate system's inertia is illustrated by the lower curve in Figure 2, which shows the temperature development if the concentration of greenhouse gases is maintained at the year 2000 level. Calculations based on the climate models show that the temperature will increase by 0.4-0.8 °C in any case. This is because the Earth's climate – and especially the temperature in the oceans – is still out of balance with the present level of greenhouse gases. The climate will therefore continue to warm, regardless of how the world and our emissions develop.

10. Regional climate changes

However, what is crucial for the effects of climate changes is not how the global average temperature develops but how temperature and precipitation develop regionally. Calculations based on the climate models show large regional changes occurring basically everywhere around the world. Warming above land will be higher than above water, and consequently higher than the global average. The temperature increase over land is usually 50 per cent greater than the global mean value. Moreover, the increase in temperature is much greater during winter in the Arctic, usually twice the global mean, which is largely due to the fact that the warming reduces the amount of ice and snow (see Box 3).

Significant changes will also occur in the distribution of precipitation. The general picture is that it will become drier in areas which are dry at present and even wetter where it already rains a lot. In addition, the dry areas will spread, with increased risk of drought in many places. This is particularly true in the dry tropics and subtropics, while increases in rainfall will be seen at higher latitudes in cooler climates. Where rainfall increases, there will be a greater risk of flooding.

The changes in the atmosphere's circulation will mean that the storm paths in the middle latitudes will move slightly further towards the poles. At the same time, calculations suggest that the maximum wind speeds in storms above the sea will increase, leading to a greater frequency of very intense and destructive hurricanes.

More extreme weather

An enhanced greenhouse effect will not just lead to a generally warmer climate, it will also result in changes in the frequency, intensity and duration of extreme weather events. Model calculations show that there will be more and longer-lasting heat waves, but also heavier precipitation. The model calculations show increasing precipitation intensity across most of the Earth, but also that the number of dry days increases. This accords with observations of climate changes over the past 50 years, and is linked to the intensification of the hydrological cycle which stems especially from the fact that higher temperatures enhance evaporation and the maximum water vapour content in the atmosphere before clouds form. When evaporation is limited (e.g. due to dry soils), this leads to less rainfall, whereas it leads to higher rainfall where evaporation is not limited by water availability.

All in all, this increases the risk of both flooding and drought in many places worldwide. Again, this is in line with what has been observed over the past 50 years, where the frequency of flooding has increased throughout almost all of Europe, while periods of drought have become more extensive, particularly in southern Europe. Similar changes are seen across the globe.

Rising sea levels

When the temperature increases as a result of anthropogenic emissions of greenhouse gases, two factors can contribute to rising sea levels worldwide. On the one hand the water expands as a result of being warmed, and on the other glaciers and ice caps melt in a warmer climate.

The likely range for the increases in sea levels worldwide during the twenty-first century is reported by IPCC as 15-59 cm depending on the chosen emissions scenario (see Table 2). The thermal expansion of water is responsible for 70-75 per cent of this increase. Recent studies suggest that the ice, especially on Greenland, will melt at a faster rate. However, these studies are still regarded as being very uncertain and are therefore not included in the IPCC's estimates in Table 2.

Sea levels worldwide during the previous interglacial period (the Eemian

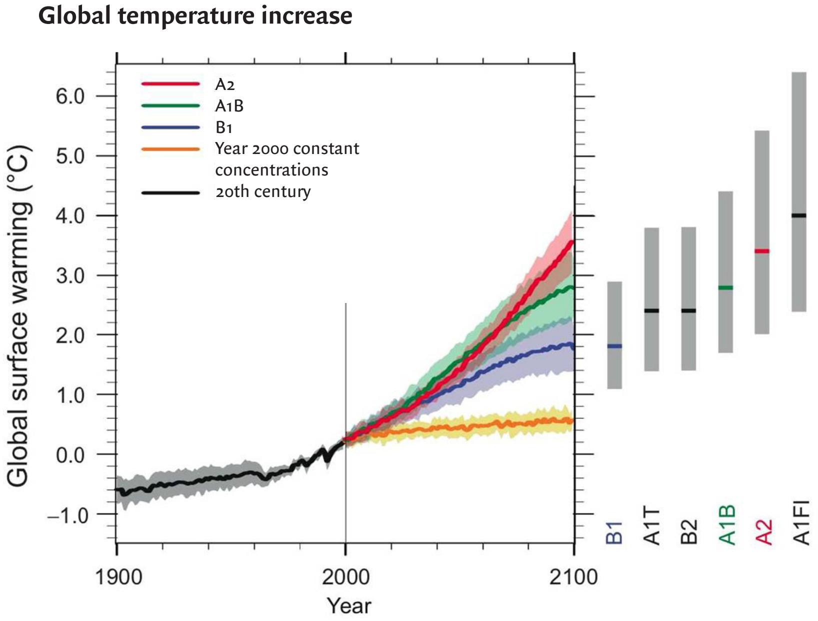
Interglacial) 125,000 years ago were probably four to six metres higher than during the twentieth century, probably due to the polar ice caps melting. It is therefore likely that the melting of the ice caps on Greenland will contribute significantly to rising sea levels in the coming centuries. However, thousands of years may pass before the Greenland ice sheet has melted away completely. Once so, sea levels would have risen by 7 metres.

Uncertainties

There is no doubt that the Earth's climate is changing towards a warmer and more extreme climate. There is also no doubt that at least the majority of the observed climate change is due to anthropogenic emissions of greenhouse gases.

However, considerable uncertainty remains on how climate will change in future. This is not so much due to the obviously chaotic nature of the weather systems or the natural fluctuations in the climate caused by changes in solar radiation or volcanic eruptions. Rather, the uncertainty is largely attributable to our current lack of understanding of the feedback mechanisms

Figure 3. Model calculations of the global rise in temperature from 1900 to 2100 for three emission scenarios (see Box 3) as well as for the hypothetical situation where the atmospheric content of greenhouses gases remains constant at 2000 levels. All temperatures are shown relative to the mean temperature for 1980-1999 (Solomon et al. 2007).



in the climate system. This can make the climate change both larger and smaller than the present projections.

In terms of how society adapts to climate changes, reliable projections of temperature and precipitation distribution play a key role at regional level. In many cases, it is also important to have detailed information about changes in the frequency of extreme weather events such as storms, heavy rainfall and drought. Here, the climate models have improved markedly in recent years, but improvements are still badly needed.

For projections towards the end of the twenty-first century, the uncertainties regarding the future emissions of greenhouse gases are far more important than the uncertainty about the climate sensitivity. This shows that at we now have a reliable climatic basis for deciding whether we as a society must take steps to avoid the climate changes. It also shows that mankind will be forced to adapt to changes in climate – some warming is unavoidable.

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