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Special Issue

Climate and Climate Change

Aktuel Naturvidenskab

Special Issue:
Climate and climate change

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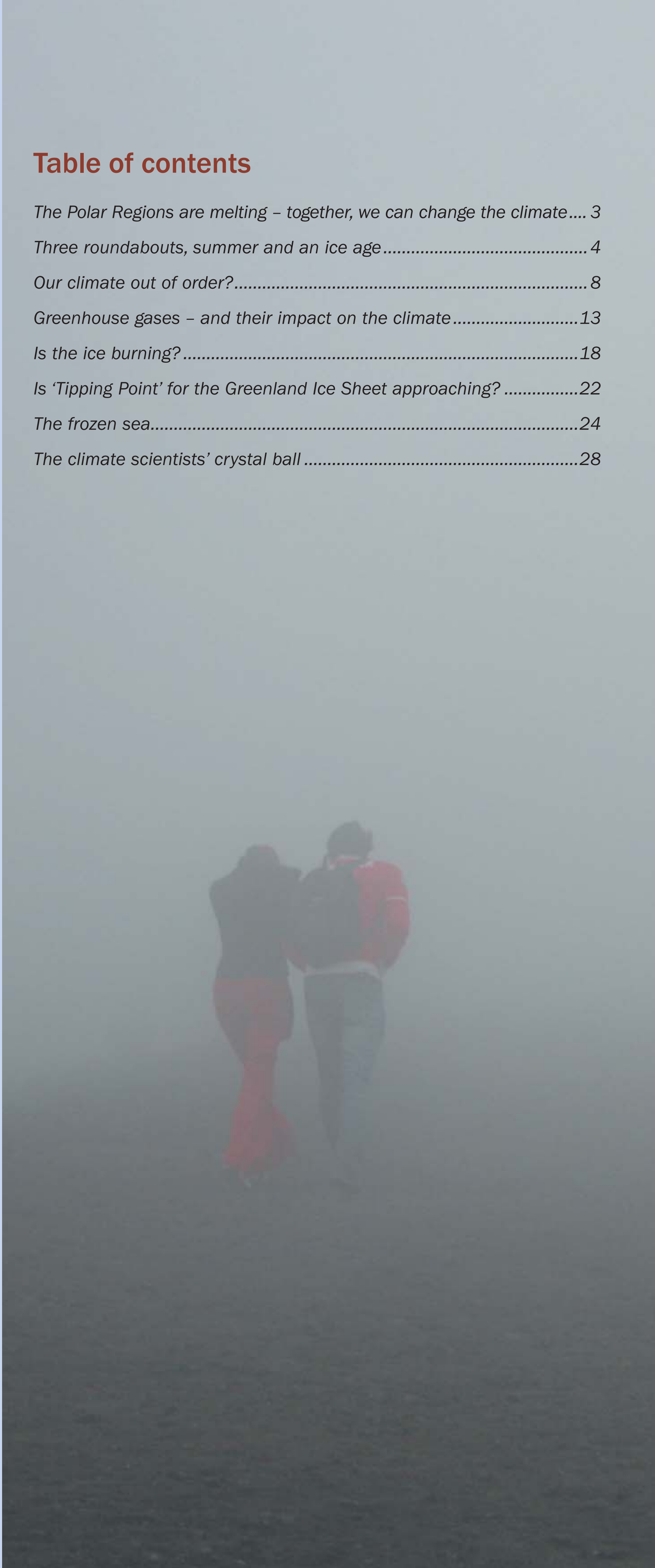

Photo: Carsten Broder Hansen

The Polar Regions are melting

– together, we can change the climate

By Dr. Sebastian H. Mernild, Ph.D.
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■ Man-made emissions of carbon dioxide to the atmosphere from fossil fuels have never been greater than they are today. Since the first systematic measurements in 1958 of the atmospheric concentration of carbon dioxide on mountain peaks around the globe, the concentration has increased to the present level (October 2009) of 388 ppm (parts per million), despite the Kyoto Protocol and global climate and energy policy plans. Meanwhile, according to the Intergovernmental Panel on Climate Change (IPCC) projected scenarios, the climate and the impacts of climate change are following worst-case.

Warming will continue models predict

The climate is changing! The global average temperature has in the last 50 years increased approximately 0.6 degrees Celsius. The change in climate has been greatest in the Arctic as dwindling amounts of snow and ice cover enhance the effects of warming. At the same time a cooling of the stratosphere has been observed. These observations are by the book, if the warming of the last 50 years is caused mainly by the greenhouse effect. For the same period an almost unchanged and only very slightly increased solar activity has been observed of only 0.12 W m^{-2}, which corresponds to 8 percent of the total estimated anthropogenic climate impact. It is therefore without scientific evidence and extremely speculative to let the almost unchanged activity from the sun (over the past five decades) appear as the main reason for global warming. In contrast, it is reasonable to accept that the increasing temperatures are explained by the increasing concentration of carbon dioxide in the atmosphere throughout the same period.

Climate model studies based on moderate scenarios for the evolution of the atmospheric content of greenhouse gases suggests that the present warming will continue in the future. An average temperature increase of 5 degrees Celsius by the end of 2100 is not unrealistic. According to the models, it is for example expected that the rise in temperature for East Greenland will be as high as 12 degrees during winter, an increase that will enhance the already accelerating glacier melt.

It is important to stress that we on the one hand, with increasing certainty can detect and quantify the anthropogenic impacts on the environment, and on the other hand can understand more and more of the dynamics of the earth system, which gives rise to year-to-year variability and long term periods with decreasing temperatures. This is caused by a natural dynamic oscillation, for example, by changes in ocean currents and surface albedo, which is influenced by a changing snow and sea ice cover. Both the present and future projected climate must therefore be viewed in this light, and the anthropogenic warming and its processes taken seriously during a longer-term documentation over several decades.

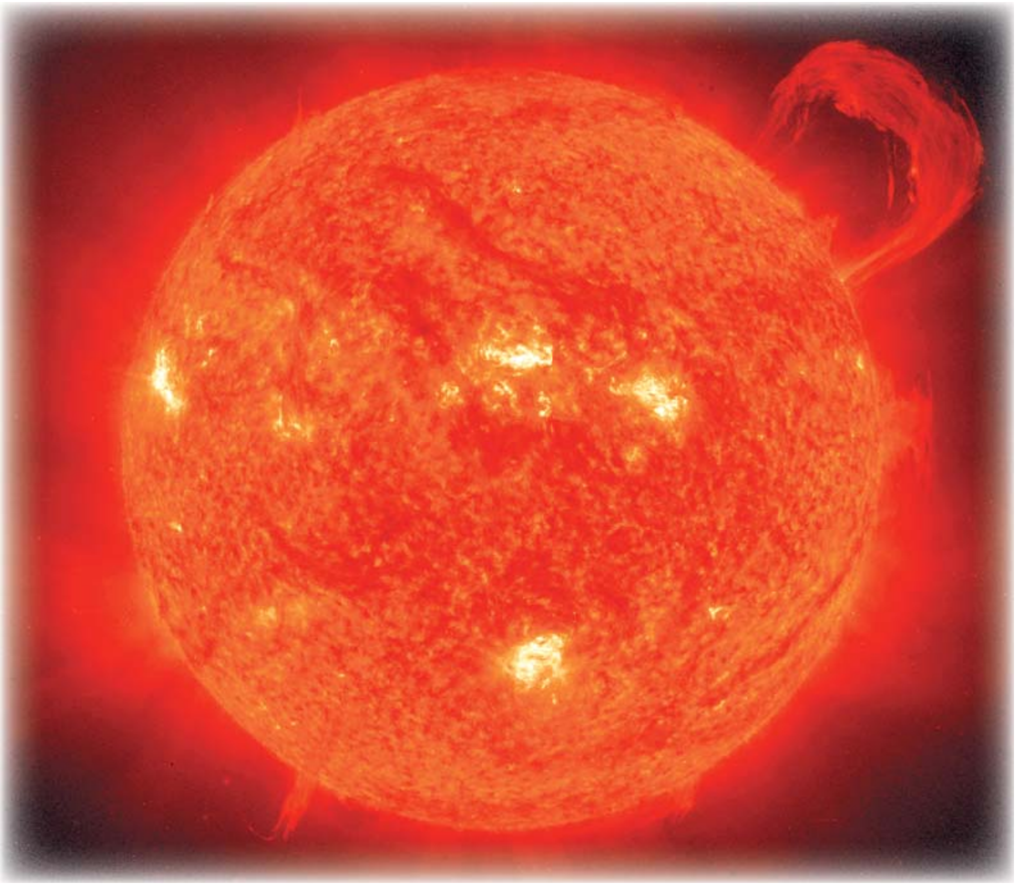
Time to act

An increasing future global population, with the expectations of increasing wealth and economic growth will continue to raise the concentration of greenhouse gases in the atmosphere. The consequences of a warmer climate are significant in many aspects. An enhanced regional warming in the Arctic, which until now has only been a problem and a challenge for the sparsely populated Arctic, will in the near future become a global problem. Where the Greenland Ice Sheet at present, according to latest research, is losing about 250 km^3 per year, the projected average net loss in the year 2080 will increase approximately twofold. At East Antarctic as well, the ice sheet has started melting faster than previously believed. Millions of tons of ice have melted since 2006. The mass loss from the Greenland Ice Sheet and Antarctica contribute at the moment around 25 and 10 percent, respectively, of the global sea level rise of about 3 millimeters a year, a rate of sea level rise almost twice as high as the average over last century. The most recent improved computer models used to calculate changes in sea level indicate that the overall effect of the melting ice, including the thermal expansion due to higher ocean temperatures, may increase the global sea level between 0.8 to 1.9 m by 2100. Even with low carbon dioxide emissions to the atmosphere one can expect an increase in sea level of about 1 meter, which is considerably higher than the IPCC estimate of 18 to 59 cm for the same period. Unfortunately, sea level rise is not expected to end by 2100.

We are at the point where the trend in climate change seems clear – the Polar Regions are melting, and in many cases the trends are following a worst-case scenario. Climate change is not only a polar issue, but a global issue, which requires global solutions. Therefore, there is an urgent need for an effective global approach that reduces man-made emissions of carbon dioxide to the atmosphere and reduces the rate of temperature increase. ■

Three roundabouts, summer and an ice age

Climate variations on a long time scale such as ice ages, which come and go, can be linked to variations in the Earth's movement around the Sun. Such natural climate variations set the scene for understanding the climate from a human perspective.



Energy from the Sun is a driving force behind Earth's climate and variations in Earth's orbit around the Sun are believed to be the cause of major climatic events such as ice ages.

By Bjarne Siewertsen

■ Climate change is not strange viewed on sufficiently long term. Rather, we could from a longer perspective wonder why the climate has not changed more than it has. The climatic processes have never gone berserk in a way which made it totally impossible to sustain life on earth, such as transforming Earth into an uninhabitable, frozen planet or a barren wasteland without water.

The long term climate changes may in themselves seem very dramatic from a human perspective. Within the past one million years the norm in our part of the world has been a colder and much more inhospitable climate than we know today. The climate has alternated between long ice ages, which have covered much of Europe and North America in ice, interrupted by relatively warm and short interglacial periods.

Today we are experiencing one of these interglacial periods, and to put current concerns about global warming in perspective, one could ask whether we are actually at the dawn of a new ice age and thus faced by challenges of an entirely different magnitude? For those concerned about that downloading the latest *IPCC assessment report* (the AR4 released in 2007) must be comforting. The report states it as *very unlikely* that a naturally caused ice age will commence on Earth within the next 30 thousand years.

In order to understand short term climate development, we need to understand how the current climate situation fits into the larger context, which in recent geologic ages have seen ice ages come and go.

What exactly triggers and

ends an ice age is still open to debate, but most scientists agree that one answer lies in the cyclical variations of Earth's movement around the Sun.

These variations are collectively known as the Milankovitch cycles after the Yugoslav geophysicist Milutin Milanković (see box).

The shape of the Earth's orbit

Earth moves around the Sun in an elliptic orbit. How much the ellipse departs from circularity is known as the eccentricity of the ellipse and varies over time due to the gravitational pull of the other planets in the Solar system (see box). This variation is cyclical with the orbit going from being almost circular to its maximum eccentricity and back again, over a term of 95,800 years.

The point of the orbit where Earth has the greatest distance to the Sun is called the aphelion, while the perihelion corresponds to the point where the distance is the least. Presently perihelion occurs around January 3rd when Earth's distance to the Sun is around 146 million kilometers, while aphelion is around July 4th and we are 151 million kilometers away from the Sun.

When the movement around the Sun achieves its greatest circularity, the distance to the Sun at aphelion and perihelion is almost identical, and when the ellipse has maximum eccentricity, the solar irradiance between aphelion and perihelion varies by as much as 30 percent.

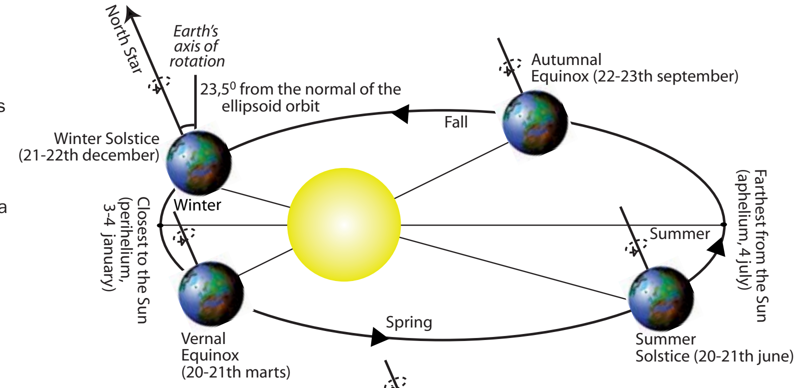
Current solar irradiance is seven percent lower in June than in December.

The Earth's axial tilt

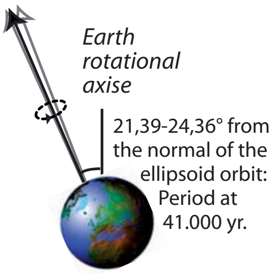
Earth does not revolve just around the Sun. In a day it completes a rotation around itself. But the Earth axis of rotation is not perpendicular to the plane of its orbit. The tilt is currently 23.44 °, but varies cyclically from 21.39 ° to 24.36 ° and back on a term of 41,000 years. The second cycle is called the inclination (see box).

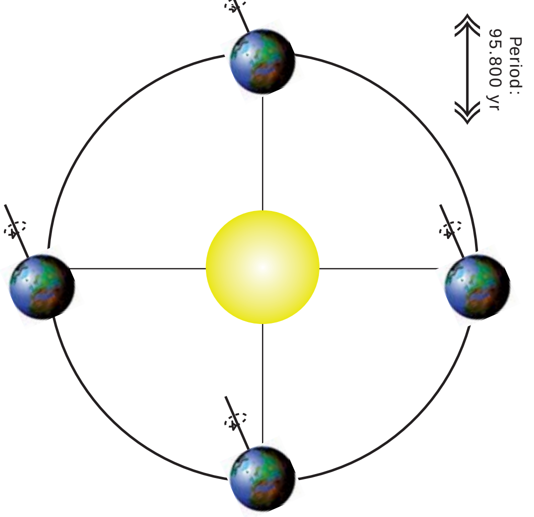
Eccentricity and inclination

Earth moves around the Sun in an elliptic orbit. Earth's orbit around the Sun varies from being nearly circular to moderately elliptical. Going through a cycle from a circle to an elliptical orbit with maximum eccentricity and back again requires a term of approx. 100,000 year. →



The Earth's axial tilt
Earth's axis of rotation in relation to its orbit varies between 21.39 and 24.36 degrees. This cycle is called the inclination and has a term of approx. 41,000 years. ↓





Graphics: Bjarne Siewertsen, 2007

Croll og Milankovitch

The idea that Earth's movement around the Sun and around itself could have a cyclical effect on Earth's climate is now old news. It was first proposed by the Scottish naturalist James Croll (1821 - 1890) in the late nineteenth century.

Croll said that the best conditions for the spread of ice sheets occurs when winters are coldest, i.e. those winters when Earth is farthest from the Sun in a highly eccentric orbit. However, he could not get his calculations for the beginning and ending of ice ages to fit with the geological evidence, which piled up at the turn of the century, and his theory was discredited.

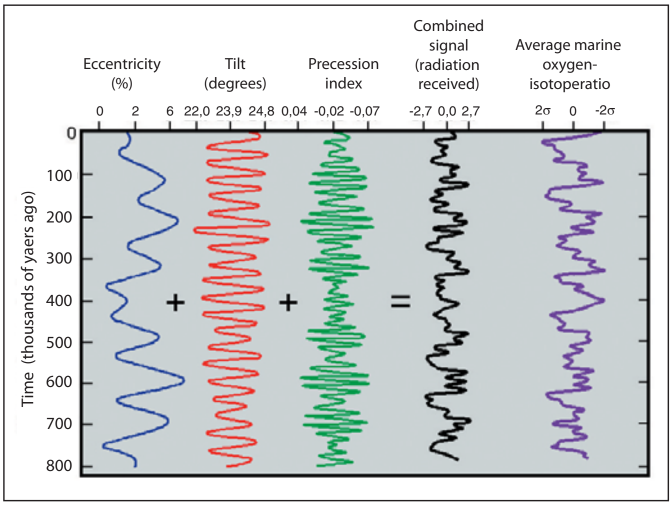
In the early twentieth century, however, the theory was adopted and further developed by the Yugoslav geophysicist Milutin Milanković (1879-1958) who, with the German climatologist Wladimir Peter Köppen (1846-1940), figured out where Croll's error lay. The two proposed that cool summers were decisive in triggering an ice age, since during a cold summer the melting of polar ice caps did not outweigh the accumulation of ice during winter.

Milanković and Köppen maintained that it had to be the summer irradiation on the northern hemisphere, which was the determining factor. Only in the northern hemisphere do the land masses such permit the build up of continental ice sheets.

Milanković's great achievement was that he subsequently calculated the variation of irradiation as a function of season and latitude over the last one million years, which he did by hand. It took him 20 years, and in 1941 he published a 633-page book titled "Canon of Insolation of the Earth and Its Application to the Problem of the Ice Ages".

Milanković never had the chance to see the geological evidence for these cycles. In 1976, the marine geologists Jim Hays, John Imbrie and geophysicist Nick Shakleton succeeded in demonstrating that glaciations closely correspond to 100,000, 41,000 and 22,000 year cycles, by studying oxygen isotopes in deep sea sediments, dating more than 300,000 years back in time.

Hays, Imbrie and Shakleton examined the hard parts of calcareous invertebrates, which constitute the bottom sediments and traced an oxygen-isotope composition of chalk, which showed these glacial cycles. The fact is that oxygen-isotopic composition in both the ice and in the limestone varies according to how much or little ^{18}O, is bound in ice sheets.



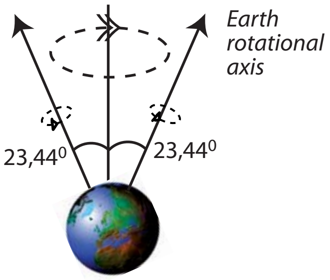
The graph shows the cumulative effect of the three Milankovitch cycles (eccentricity, inclination and precession) as variations in the amount of radiation the Earth receives from the Sun. To the right is a curve of the oxygen isotope relation O^{18}/O^{16} as measured in the cores of marine sediments. This ratio is indirect evidence of temperature.

The less the tilt is, the less is the difference between summer and winter. If the angle was 0° and the axis of rotation was perpendicular to the plane of its orbit, the daily solar irradiation would remain constant throughout the year on any one location on Earth (except for the variations due to eccentricity).

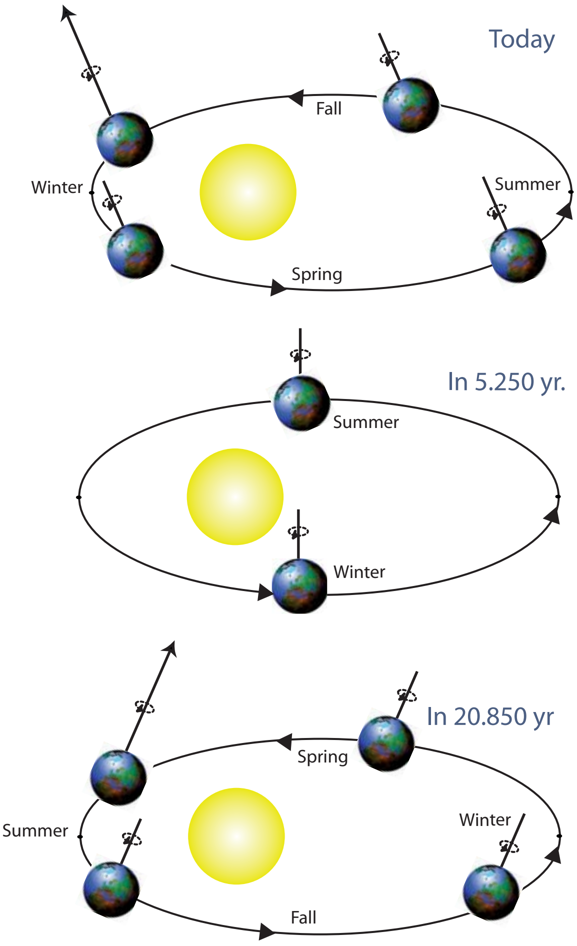
Conversely, a steeper slope will result in an extension of the period of polar nights.

Changes in the axial tilt have great impact on the length of the days (direct solar irradiation) at high latitudes during summer. A small tilt will contribute to the build up of extensive ice sheets, while a greater angle of tilt would increase the melt from the ice sheets.

Precession



The direction of Earth's axis of rotation (not to be confused with the angle of the axis of rotation, or inclination) varies over time. Over a term of 21,700 years the axis swings around in a conical motion, like that of a spinning top. This phenomenon is called precession.



Graphics: Bjarne Siewertsen, 2007

The direction of the Earth's axis

Direction (in this case not the angle) of Earth's axis of rotation also changes cyclically. Over a term of 21,700 years the axis swings around in a conical motion, like a spinning top (see figure). During this period, it changes direction, but not tilt, so that in 10,500 years summer will occur when Earth is closest to the Sun. This will make summers warmer than they are now, but also shorter. This third cycle is called precession.

According to Kepler's 2nd law a line joining a planet and the Sun sweeps out equal areas during equal intervals of time. Thus, currently winters (which are closer to the Sun than the summer) are shorter than summers. Similarly, summers will be shorter than winters in some 10,500 years.

However, conditions will be completely opposite in the southern hemisphere.

When summer is replaced by an ice age

As we have seen summer and winter are the product of inclination. But what about larger climatic events such as the coming and going of ice ages? This matter is somewhat more complicated.

The combined effects of eccentricity, inclination and precession, create very complex irradiation variations along Earth's latitudes (see figure).

Large ice sheets began to develop 2.75 million years ago on the northern hemisphere. Ice sheets built up and melted within a 41,000 year term (and singular incidents every 22,000 years) or in other words according to Earth's inclination. This trend continued while the temperature in general decreased on the northern hemisphere.

The cooling and the impact of the inclination cycle were predominant until some 900,000 years ago, when a threshold apparently was reached and the ice caps no longer melted away after the inclination cycles. Thus the

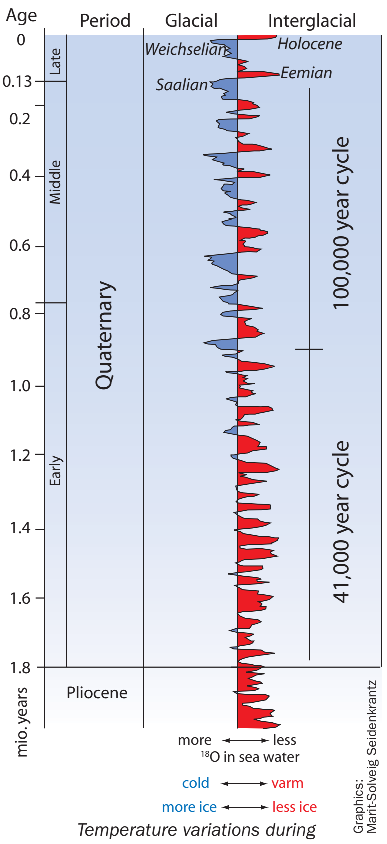
Mapping of the climate of the past

Knowledge of the climate of the past is important in order to understand today's climate. While charting present climate can be done by measuring important parameters such as temperature and precipitation, one must resort to indirect evidence when determining the climatic conditions in geological history. Such geological evidence of climatic conditions can for instance be the geographical distribution of geological deposits, which point to a warm climate such as deposits of coal, salt and sediments typical of deserts - or to a cold climate such as glacial deposits. In these deposits, there will often be remnants of past flora and fauna, which can also tell scientists whether it had been cold or hot at that time and place.

When examining these sediments one must naturally take into account that the continents have shifted over time, it is therefore possible to find depositions originating from tropical conditions in the Arctic underground.

You could say that the closer you come to the present date, the better the geological evidence of climate variability is – this is in part because of the accessibility of deposits of recent date, which are relatively more common and because in terms of land mass displacement there are fewer sources of error. Finally, it is also possible to make more accurate dating of newer sediments, because there are more dating techniques available when the deposits are more recent. In the last decades, interest has especially turned towards ice core drilling in Greenland and Antarctica, since it is possible to interpret climate variability on a yearly basis several hundred thousand years back in time. One of the main methods for reconstruct the temperature of the past is by measuring the amount of the oxygen isotope 16O (which is the general oxygen isotope, and represents over 99% of the oxygen on Earth) and its heavier – and rarer counterpart – 18O. Since the light oxygen isotope ^{16}O evaporates more easily than ^{18}O, there will be less of the heavy isotope present in the atmosphere during cold periods than in warm periods. The colder the atmosphere at a given time, the less ^{18}O will therefore be present in the precipitation as well. In the ice sheets, the relative volume of the two oxygen isotopes reflects the atmospheric temperature at the time the layer was formed.

Calcareous organisms such as mussels and coral also accumulate oxygen isotopes in their shells while alive. Therefore, analysis of the chemical composition of the hard parts of calcareous organisms also tells scientists about the temperature conditions, while the organisms lived.



Temperature variations during 1.8 millions years.

Graphics: Marit-Solveig Seidenkrantz

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eccentricity began to take control of the climate and ice ages have since then occurred with 100,000 year intervals. In addition to the 100,000 year cycle the lesser 40,000 and 20,000 years cycles manifest themselves as shorter cold spells.

Scientists generally agree that the Milankovitch-extremes can trigger ice ages under various conditions. But there is also consensus that something more is required. The Milankovitch cycles interact with the quantity of dust and other particles in the atmosphere, as well as the relation between the continents and how ocean currents affect the climate system and change rainfall patterns.

A cornerstone of our understanding

There are several small blanks that have not been included in the above, since they are not central to an understanding of the mechanics of the Milankovitch cycles. Earth, for instance, does not behave quite like the spherical body, as assumed in Kepler's laws, and we have not looked in depth upon the gravitational effect of the other planets in the solar system.

The fact that the major-axis of Earth's orbit is not stationary but moves in relation to fixed stars is also unaccounted for here. This affects the length of the precession term, but not the length of the climatic cycles that Earth undergoes.

As explained, the Milankovitch cycles are not the ultimate explanation of climate behavior. But understanding that Earth's movement around the Sun and its own rotation has a decisive impact on Earth's climate in the long term is now one of the cornerstones of our understanding of Earth. ■

Further Reading:

Ahrens, C.D., 2000: Meteorology today, Brook & Cole.

Dansgaard, W, 1989: Istiderne og Croll-Milankovitch effekten, Naturens Verden

Dawson, A.G., 1992: Ice Age Earth, Routledge.

Lowe, J.J. & Walker, M.J.C., 1984: Reconstructing Quaternary Environments, John Wiley & Sons.

Our climate out of order?

By comparing data from geological studies to modern climate data, we believe that we are now able to distinguish between natural climate variations and anthropogenic climate change. The results indicate that the last 20-30 years of global warming cannot be explained by natural processes.

By Marit-Solveig Seidenkrantz,
Antoon Kuijpers and
Torben Schmith

■ Nowadays we hear one doomsday prophecy after another about anthropogenic climate change. But there are also those who would dispute that we humans have any effect on the climate. The debate sometimes descends into trench warfare, where nuances are not tolerated. Hence the need to better differentiate between natural and anthropogenic climate change arises. This has now been accomplished through comparison of geological studies of past climate and modern weather data. These studies suggest that although a significant proportion of the global warming of the 20th century probably was caused by natural variations, the significant warming that has happened over the last 20-30 years cannot be explained by natural processes alone. There is in fact strong evidence indicating that the climate system is undergoing a fundamental change.

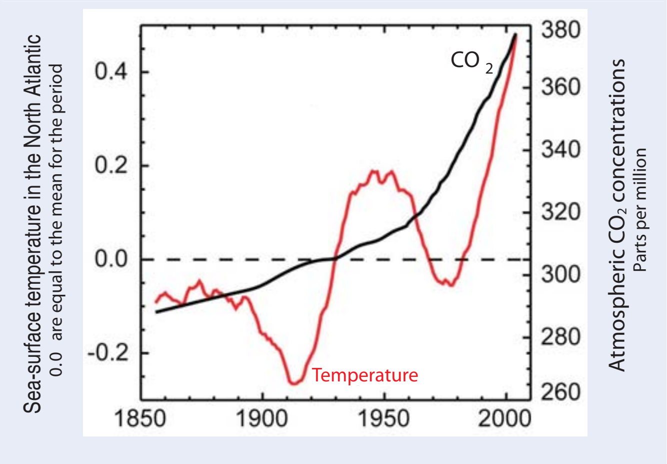


Figure 1. Sea-surface temperature in the North Atlantic compared with atmospheric CO_2 concentrations since 1856.

More than one explanation for climate change

In the ongoing debate about the significance of the current climate changes, the discussion is mostly limited to a comparison of the evolution of the climate during the last 100-150 years. This is because a systematic recording of climate data (such as temperature, precipitation and pressure) first began in the middle of the 19th century. One would also think that 150 years is ample time to get a good picture of how a "normal" climate behaves. But it is often forgotten that the middle of the 19th century was precisely the time when the so-called Little Ice Age, which was the coldest period in of the last 6000-8000 years, came to its conclusion.

The long-term trend of the last 150 years has been a warming of the climate, but there have also been cold periods – most recently in the 1960s. We know that the concentration of greenhouse gases in the atmosphere is of great significance to climate. In Earth's history there have previously been periods with very high concentrations of greenhouse gases in the atmosphere. In general these periods were also significantly warmer than is the case today. But if we compare the temperatures of the 20th century with the amount of CO_2 in the atmosphere (see figure 1), we can see that there is no directly linear relationship. This means that greenhouse gases are not necessarily the only explanation for climate changes and we must therefore look for additional explanations.

Considerable variations over the last 2000 years

If we are to understand the longer-term trend of the climate, we need to study the past through geological data. Our climate has been characterized by significant variations over the last 2000 years. The best-known

It requires a lot of equipment and work to retrieve samples from the ocean floor, especially if the layering is to be kept intact.

Photos:
Esben Villumsen Jørgensen
Anja Kinnberg Gunvald
Marit-Solveig Seidenkrantz

phenomena, which are known to have left a mark on European cultural history in particular are the Roman Warm Period (about 500 BC - 400 AD), the European Dark Ages Cold Period (400-700 AD), the Medieval Warming (800-1200 AD), the Little Ice Age (1350-1850 AD) and finally the 20th Century Modern Warming which began approximately in 1850. Current climate changes do not represent a simple change from a stable "normal" climate, but they should be seen in a context of generally unstable climatic conditions, which have shaped the Earth over the last millennia.

Only by understanding the processes, contexts and timescales for these climatic variations, it is possible to understand how and why the climate is changing now and tomorrow. One of the partly unresolved issues is to be able to distinguish between natural climate variability and anthropogenic influences. By comparing geological data with instrumental measurement data we have managed to make a first step in this direction.

Samples from the ocean floor in tubes and ready for storage and for further study at home in the laboratory.

The North Atlantic Oscillation

A number of theories have been proposed to explain the current climate changes. They include variations in solar radiation, sulphur gases from volcanic eruptions, emissions of greenhouse gases and large scale variations in oceanic circulation. It would be too extensive to discuss all of these theories here, so we will focus on only one of the major natural mechanisms: *the North Atlantic Oscillation (NAO).*

"In Greenland all winters are severe, yet they are not alike. The Danes have noticed that when the

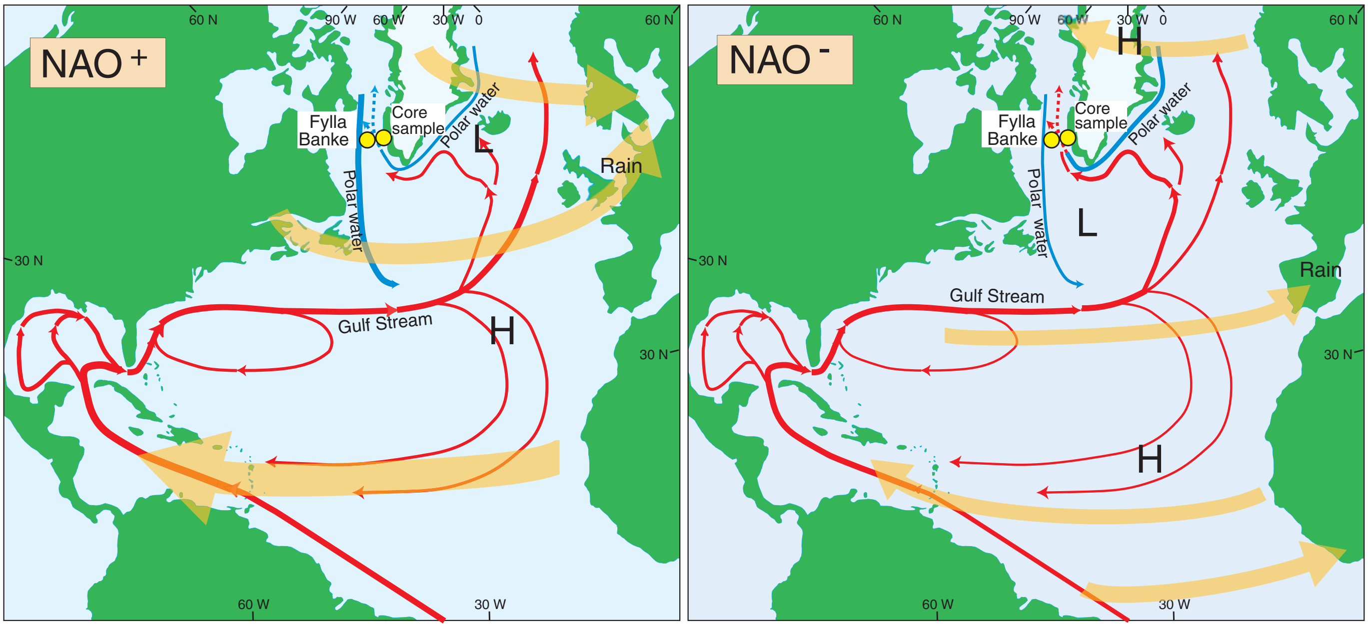


Figure 2. Currents and the North Atlantic Oscillation: ocean currents (red arrows = warm water, blue arrows = cold water), wind direction (orange arrows) and location of high pressure (H) and low pressure (L) in the North Atlantic during NAO^+ *(left) and* NAO^- *(right) situations. The studied cores near Nuuk and the oceanographic station at Fylla Banke are shown as yellow dots.*

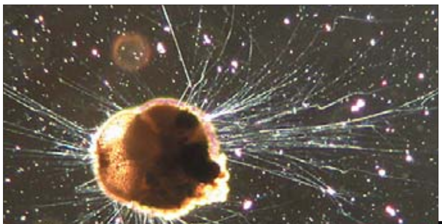
winter in Denmark was severe, as we perceive it, the winter in Greenland in its manner was mild, and conversely."

This quote is from the diary of Hans Egede Saabye, a missionary in Greenland in 1770-1778. It is one of the oldest historical sources reporting these opposing temperature pattern seen between Europe and West Greenland. Today this phenomenon is well-known and is in part a consequence of the so-called North Atlantic Oscillation (NAO), which are temperature fluctuations affecting both the atmosphere and the ocean. It is basically driven by air pressure over the North Atlantic. During the so-called NAO^+ stage there is a strong low pressure over Iceland and a strong high pressure over the Azores. This pressure difference creates strong westerly winds, moving warm air towards Denmark, especially in the winter. The westerly wind also forces the waters of the Gulf Stream closer towards the coast of Europe (Figure 2), while the coast of West Greenland is mainly washed by the cold waters of the Arctic Ocean. In some years there is a smaller difference in air pressure, and westerly winds

Foraminifera - good climate indicators

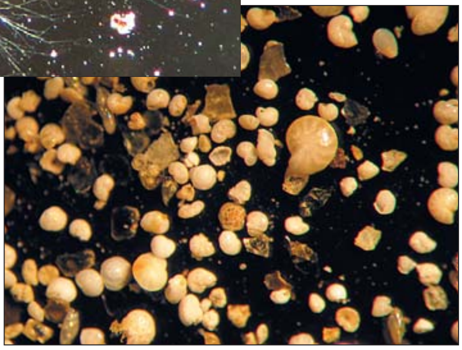
Foraminifera are microscopic, unicellular organisms belonging to the group Protozoa and in the same family as amoeba. They are a very important group of organisms representing a large proportion of all life in the ocean. The oldest fossilized foraminifera are approximately 560 million years old, but the group has probably existed for 1000 million years, and has been very successful ever since. We know of about 40,000 species, of which 10,000 are still alive - the rest being extinct. Most foraminifera vary in size between 0.04 and 1.0 mm, but are commonly between 0.1 and 0.5 mm. They consist of a slimy "body" with strands of cytoplasm, or pseudopods, which extend from the body and are used to collect or capture food. The body is usually surrounded by a shell of either lime or mortared sand that they have collected from the ocean floor. These shells are easily preserved as fossils and can be found in sediment layers going far back in time.

Based on their lifestyles foraminifera can be divided into two main groups: the planktonic species, which float freely in the water column of the open seas, and the benthic living on the seabed. The planktonic foraminifera predominantly live off phytoplankton or small zooplankton, while the benthic foraminifera also devour the remains of dead animals or plants, which sink to the bottom.



Live foraminifera with pseudopods: Ammonia Tepida

Photo: Scott Fay, UC Berkeley



Fossilized fauna from the Little Ice Age deposition from core 248260-2G from Ameralik Fjord, Greenland.

Photo: M.S. Seidenkrantz

Foraminifera represent 2.5% of all animal species that have existed throughout the history of Earth. Given that many species have risen and disappeared again foraminifera are successfully used to date layers of soil. They are also extremely useful for determining past climate and environment, since the different species make different demands of their habitat. They can therefore tell us about seawater temperature, salinity, current strength and the amount of oxygen in the sea bed – for instance whether there have been periods of oxygen depletion. That way, we can learn how ocean circulation has worked in the past and how it has affected the climate. Since foraminifera are also sensitive to pollution (such as organic matter, nutrients and heavy metals), they are also used to investigate pollution at sea.

The calcareous foraminifera also build their shell in chemical equilibrium with the seawater. This means that you can measure chemical constituents such as stable oxygen and carbon isotopes, which in turn give information about sea temperature, the extent of glacial ice, nutrient content, etc.

Photo: Colourbox

The rising temperatures cause increased calving of icebergs from glaciers in Greenland.

are weaker (the NAO⁻ stage). The Gulf Stream is to a lesser degree pressed towards Europe, and part of the warm water will swing further to the west and bring heat to West Greenland. NAO⁺ thus causes mild winters with a lot of precipitation in northwestern Europe and very cold winters in West Greenland. Conversely, the NAO⁻ triggers cold and dry winters in northwestern Europe and warmer winters in West Greenland.

Natural climate changes over the last 2000 years

Results of studies of marine core samples from West Greenland show that there have been large variations in the amount of warm Atlantic water reaching this area over the last 2000 years. Comparisons of calculations of the temperature in Europe and other parts of the northern hemisphere (Figure 3A) with estimates of water temperature off West Greenland (Fig. 3B) also show an opposed pattern. In some periods the Gulf Stream led warm water to Europe. This caused a hot and humid climate especially in Northwestern Europe during the Roman Warm Period and the Medieval Warming. In other periods, less water from the warm Gulf Stream reached Europe, but came instead to West Greenland. During these periods the European climate was colder (the European Dark Ages Cold Period and the Little Ice Age). This new research shows that the major climate changes that have characterized the last 2000 years largely were caused by changes in wind direction and ocean currents.

Recent research suggests that mechanisms other than the NAO can create variations in the strength and path of the Gulf Stream. Without going into too much detail, these mechanisms involve internal variations in the so-called thermohaline circulation, with changes in the sinking of Atlantic waters off Greenland and Labrador. These changes may last several centuries, creating changes in air temperature of a similar duration. Mechanisms such as variations in the solar radiation and El Niño Southern Oscillation seem to play a role in climate variability as well.

The 20th century warming

Modern measurements and geological data from the last 2000 years tells us that the climate, both past and present, has to a large extent been characterized by a complex interaction between atmospheric conditions and oceanic currents. The instrumental measurements also show that the 20th century has seen the climate change from being dominated by the NAO⁻ to being NAO⁺ dominated. This means that a significant part of the temperature increase probably can be explained through a natural change from a climate dominated by weak westerly winds and a modest transport of heat to Europe, to a climate characterized by strong westerly winds and an increased transport of heat to Europe.

During the recent decades, Earth's climate has, however, undergone changes even faster than before. The understanding that the geological data has given us, can be used to deter-

Figure 3 - Natural climate changes over the last 2000 years

A) Atmospheric temperature in Europe throughout the last 2000 years compared with the mean temperature for the period 1961-1990. The curve is based on a series of geological data and indicates the temperature difference from the average for the 1961-1990 period.

B) Reconstruction of sea water temperature (cold Polar / warm Atlantic) off West Greenland during the last 2000 years. This shows the clear distinction between hot water from the Atlantic and cold water from the Arctic. The result is based on the occurrence of different species of foraminifera in sediment core samples from near Nuuk. These data indicate a warming of waters off West Greenland during periods when the climate in Europe was colder than today, while seawater off West Greenland was colder than today during the periods when the climate in Europe was warm.

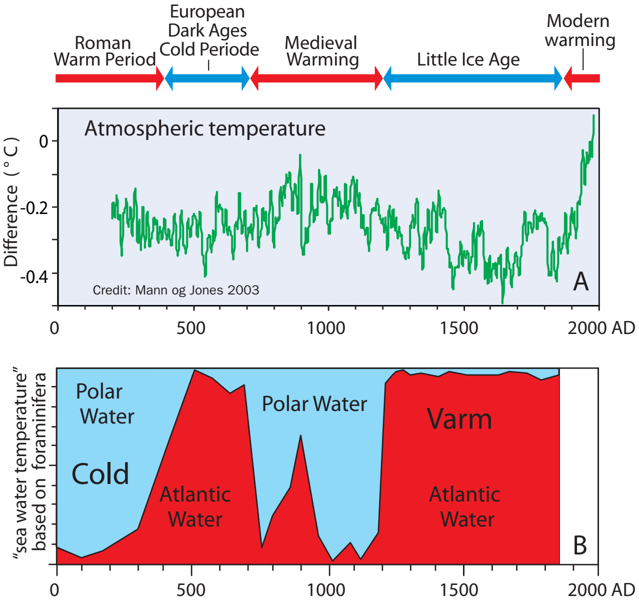



Photo: Colourbox

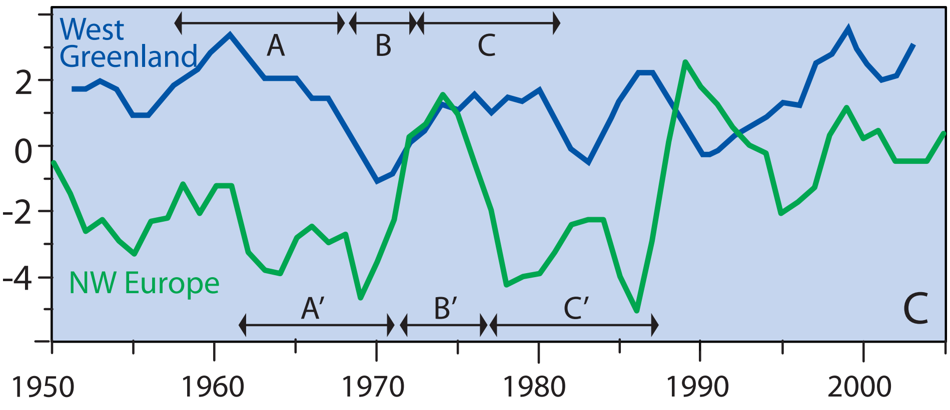
Greenland has taken a key role in raising awareness of global climate changes.

mine whether the system that has worked for 2000 years, is still active. We have therefore compared seawater temperatures in June from Fylla Banke off Nuuk, West Greenland, with the average air temperature during winter in northwestern Europe for the period 1950-2005 (Figure 4). Both curves show significant variations. Until around 1985 there was a reverse pattern between the temperature in Europe and in West Greenland, but with a delay of 4-5 years, so that a climate change in western Greenland, first would reach Europe after 4-5 years. This delay is presumably due to the inertia of the system due to the slow speed of sea currents. We can in other words say that until 1985 we experienced a climate that was ruled by the same principles that we've seen over the last 2000 years.

Man changing the climate

After 1985 that situation has apparently changed. Although the data from Fylla Banke indicates a number of variations in ocean currents, the climate in Europe no longer follows the expected pattern. It is known that the global temperature began to rise significantly during the past decades and the last three decades (after 1973) have probably been the warmest period of the last 500 years. In fact, measurements of the atmospheric pressure between Iceland and the Azores suggest that we are currently in a NAO$^-$ dominated period, which should cause a cooling, but still temperatures in Europe have risen. Meanwhile, the Sun has in recent years emitted less energy than average. Changes in the solar radiation can therefore not explain the phenomenon either.

This means that although a large part of the temperature rise that has been seen over the last 100-150 years, probably is due to natural climate variations, the significant global warming which has marked the last 20-30 years, cannot be explained through currently known natural processes. This suggests that greenhouse gas emissions are causing a fundamental change in the whole climate system.



Credit: DMI and Northwest Atlantic Fisheries Organization, Canada.

Figure 4. Sea-surface temperature (June) by Fylla Banke, West Greenland, and the air temperature in winter in northwestern Europe in the period 1950-2005. The letters A, B and C mark periods when the surface sea temperatures in western Greenland were either higher or lower than average, while A ', B' and C' show delayed and reverse variations of temperature in northwestern Europe.

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Further Reading:

Kuijpers, A., Malmgren, B.A. & Seidenkrantz, M.-S. 2009. Termination of the Medieval Warm Period: linking subpolar and tropical North Atlantic circulation changes to ENSO. PAGES News 17 (2), 76-77.

Seidenkrantz, M.-S. , Kuijpers, A. & Schmith, T. 2009. Comparing past and present climate – a tool to distinguish between natural and human-induced climate change. IOP Conference Series: Earth and Environmental Science.

Seidenkrantz, M.-S., Aagaard-Sørensen, S., Møller, H. S., Kuijpers, A., Jensen, K.G., Kunzendorf, H., 2007. Hydrography and climatic change during the last 4.400 years in Ameralik Fjord, SW Greenland. The Holocene 17 (3), 387-401.

Greenhouse gases

- and their impact on the climate

The greenhouse effect is the best understood and well mapped of the mechanisms that can lead to climate change.

By Eigil Kaas and Peter L. Langen

■ Our planet's climate is largely determined by the balance between the energy supplied by sunlight and the energy that Earth loses to space in the form of infrared radiation.

Satellite measurements show that the solar energy irradiating Earth is about 342 Watts per square meter (W/m^2). This figure is an average over the entire planet, day and night, all year around. It therefore spans from zero W/m^2 at night when the satellite is in Earth's shadow, to approx. 1367 W/m^2 in places where the sun is at its zenith. Approximately 31% of the incoming solar radiation is reflected by clouds and atmospheric particles and the planetary surface. This is also referred to as the planetary albedo, where albedo is an index of reflectivity from 0 (no reflectance) to 1, (full reflectance). The planet thus has an albedo of 0.31. The reflected radiation can be seen from satellites as upward going light. In itself it has no effect on the climate system, but the 69% of solar radiation that remains does have an impact: The remaining 236 W/m^2, are the ones which warm our planet and its atmosphere.

Photo: Peter Langen

A snow-covered surface reflects massive amounts of sunlight and therefore has a cooling effect on the climate.

Greenhouse effect

Earth loses the absorbed solar energy by emitting infrared radiation, or Planck radiation. It is known from physics (Stefan-Boltzmann Law) that the total energy emitted by a so-called black body (an excellent approximation in many applications) is proportional to a body's temperature to the fourth power. Over a long period, Earth on average emits just as much energy as it receives in the form of solar radiation, i.e. approx. 236 W/m^2. One can make a simple energy balance calculation, using the Stefan-Boltzmann Law, of what the temperature on Earth must be to maintain equilibrium between incoming and outgoing radiation (see box). Such a calculation results

Energy balance and climate sensitivity:

The Stefan-Boltzmann law says that the total energy emitted by a so-called black body is directly proportional to the fourth power of its absolute temperature:

$$E = \sigma T^4$$

Where E is *the total energy radiated per unit area per unit time* measured in W/m^2, σ is the *Stefan-Boltzmann constant* (5,67×10^{-8} W/m^2/K^4) and T is absolute body temperature measured in Kelvin.

By inserting 236 W/m^2 on the left side of the equation (i.e. the amount of energy the earth radiates averaged over time) we find that Earth should have a temperature of 254 °K (about -19 °C). This is Earth's effective temperature, T_E. That the actual temperature is higher is due to the greenhouse effect.

Simple calculation of climate sensitivity

As mentioned in the text climate sensitivity (λ) was introduced as an estimate of how large the change in global average temperature near the surface (ΔT_s) is as a function of a given energy input, i.e. forcing, ΔF , for example, as a result of increased atmospheric CO$_2$ content or a change in solar radiation. Thus we have the following relation:

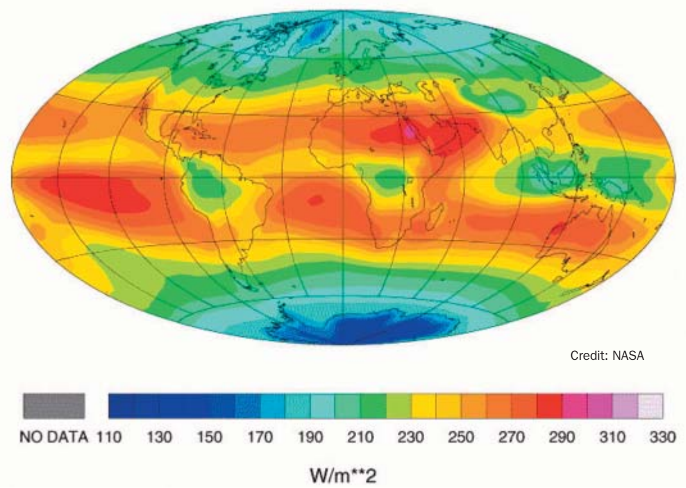
$$\Delta T_S \approx \lambda \Delta F$$

λ tells us how many degrees global temperature near the surface will increase if a change in the forcing of 1 W/m^2 is produced.

The easiest way to estimate λ is by calculating the ΔT_s-value required for upward infrared radiation to equal a given ΔF-value, i.e.:

$$\sigma(T_E + \Delta T_S)^4 - \sigma T_E^4 = \Delta F \quad \text{or} \quad \Delta T_S = \sqrt[4]{\frac{\Delta F + \sigma T_E^4}{\sigma}} - T_E$$

Inserting a forcing of ΔF of 1 W/m^2 produces a ΔT_s = 0.269 K and thus a sensitivity of $\lambda = \Delta T_s / \Delta F$ = 0.269 K/(W/m^2).
A λ-value of 0.269 is very (actually too) small, since we have not included the significance of feedback mechanisms.



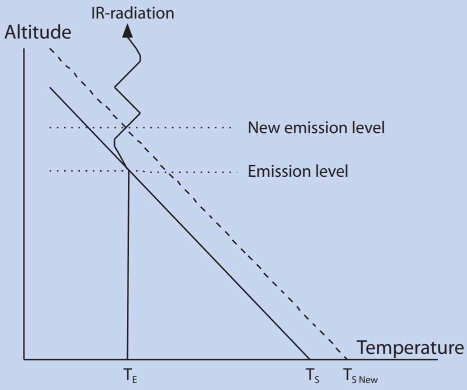
Credit: NASA

Satellite measurements of long wave radiation from the Earth Radiation Budget Experiment. The subtropical areas which have very dry air and few clouds are characterized by having a very high emissivity, since radiation originates from hot layers in the lower atmosphere. Along the equator, where there is more humidity, rising air and many high clouds, we find areas with very low emissivity, since part of the radiation comes from high and cold clouds. For instance, the mean annual radiation in Indonesia is about the same as in northern Norway. Clouds and water vapor move radiation levels up in the colder atmospheric layers, and radiation does therefore not directly reflect the actual surface temperature.

in a temperature of 254 °K (about -19 °C), which is *Earth's effective temperature (T_E)*. This temperature is some 34 °C lower than Earth's actual average surface temperature *(T_S)* which averages +15 °C. Since this energy balance calculation offers such an erroneous estimate of Earth's surface temperature, it is evident that a very effective heat preserving mechanism has been omitted. This mechanism is the greenhouse effect. Thus, the greenhouse effect is essential to life as we know it to be able to exist on Earth.

The mechanism behind the greenhouse effect

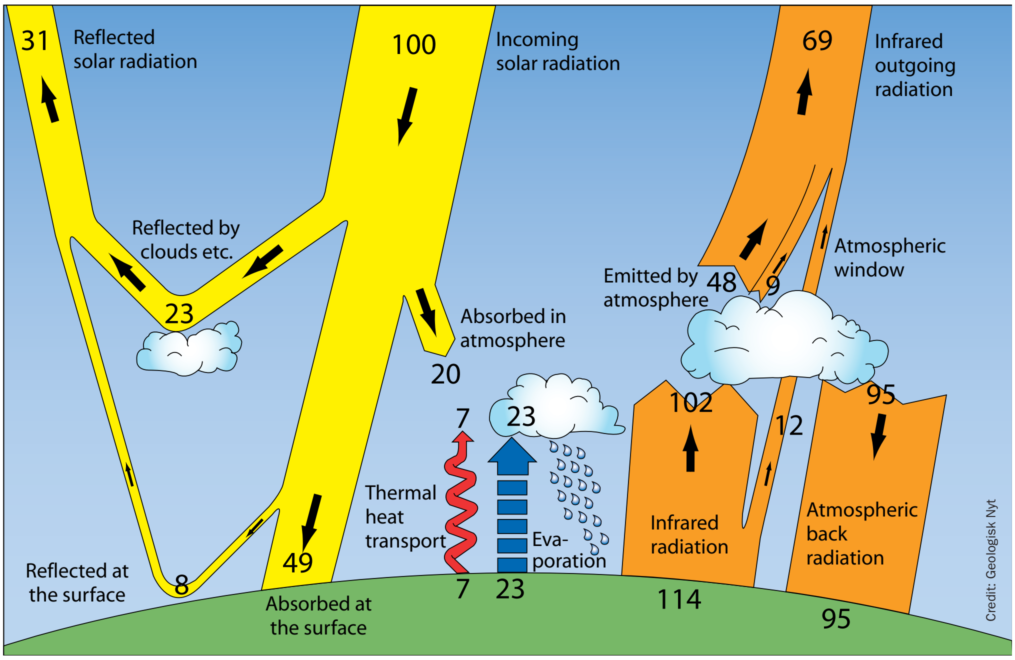
Our calculation of the effective temperature of Earth is an excellent starting point for understanding the greenhouse effect. Some of the gases that make up our atmosphere, for example, water vapor, carbon dioxide and methane, and some types of clouds are able to absorb some of the upward infrared radiation reflected by the planets surface. When these gases and clouds lose the absorbed radiation it is emitted in all directions as Planck radiation, i.e. half of the energy is emitted towards the surface and the other half into space. That means that, from a space perspective, Earth does not emit infrared radiation from its surface, but rather from the greenhouse gases and from the clouds in the atmosphere. Since the atmospheric temperature decreases the higher we get, greenhouse gases and cloud droplets, which are the same temperature as the surrounding atmosphere, emit lower temperature radiation than the planet's surface. Due to the greenhouse effect, the radiation that Earth and its atmosphere emit to balance the incoming solar radiation stems from higher and colder atmospheric layers, thereby allowing the surface to be warmer than it would otherwise have been. On average, this is the precise level at which the temperature is the effective temperature of 254 °K (at a height of some 5 km). From this level temperatures approximately increase by 6.5 degrees per km as we move downwards in the atmosphere and we can thus determine what the temperature



Schematic illustration of the enhanced greenhouse effect. When incoming and outgoing radiation are in equilibrium, emission levels have the effective temperature, T_E. Following the temperature curve we obtain the surface temperature, T_s. If the amount of greenhouse gas emissions is increased and the atmosphere becomes "denser" (as seen from an infrared perspective), the level of radiation is moved upwards, whereby the atmosphere radiates from a colder temperature and hence with a lower intensity as well. The system is now no longer in balance, and it will warm up to the new emission level T_E, and the surface level thereby rises to $T_{s,new}$.

will be at surface.

If we increase the amount of greenhouse gases in the atmosphere, the level at which infrared radiation is emitted will become higher, and will come from a lower temperature (see figure). This means that the amount of outgoing infrared radiation is reduced and the system will have an energy surplus, since the incoming solar radiation remains unchanged. This generates a warming of the atmosphere, and at some point in time the warming will be so great that the temperature at the new level from which radiation is emitted will again reach the effective temperature (T_E). As atmospheric temperature change with height remains unchanged, the surface temperature will increase, since the radiation level now lies at a greater distance from the surface. This is the warming we expect to experience as a result of the increase in the quantity of atmospheric greenhouse gases.



Credit: Geologisk Nyt

One of the most recent estimates of energy flows as a percentage for the entire planet. 100% corresponds to the average incoming solar radiation of 342 W/m² during the day and over the year at the top of Earth's atmosphere.

Photo: Lars Andersen

Photo: NASA

Cirrus clouds (left) often have a warming effect on the climate because they provide a major contribution to the greenhouse effect and have small albedo. Stratocumulus (right – here seen from above) have a strong cooling effect on the climate because their contribution to the greenhouse effect is rather small, while they usually have a very high albedo (they are very white when seen from above).

Carbon dioxide has relatively large role

The main greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), CFCs and ozone (O_3). It is impossible to rank the different greenhouse gases and clouds in an unequivocal way by their contribution to the greenhouse effect. However, one can in very broad terms say that the relation between the three main contributors to the natural greenhouse effect, namely water vapor, clouds and carbon dioxide is about 2-1-1.

It may come as a surprise that carbon dioxide plays such a relatively large role, considering that this gas is present in only very small quantities when compared to water vapor. The reason for this is, that water molecules are not nearly as effective at absorbing and emitting infrared radiation as carbon dioxide molecules are. Carbon dioxide primarily absorbs infrared radiation at wavelengths from 12-18 µm. Water vapor absorbs at many different wavelengths but does so less effectively. At the wavelength range from 8-12 µm greenhouse gases generally absorb and emit very little radiation. These wavelengths are called the atmospheric window, because radiation can pass relatively unhindered through the atmosphere, though not as freely as visible light does. Clouds absorb and emit infrared radiation at all wavelengths, and therefore also in the atmospheric window.

An increase in atmospheric carbon dioxide gives a slightly larger increase in the greenhouse effect in the tropics than it does at high latitudes.

Climate Sensitivity

A warming caused by an increase in greenhouse gas concentrations (or any other change of climate parameters) is defined by a number, called the climate sensitivity.

Climate sensitivity tells us how many degrees global temperature will change near the surface if a change in the power supply of 1 W/m² occurs. Such a change in energy intake may be due to a sudden increase in the concentration of CO_2 and other greenhouse gases in the atmosphere as well as due to an increase in solar radiation.

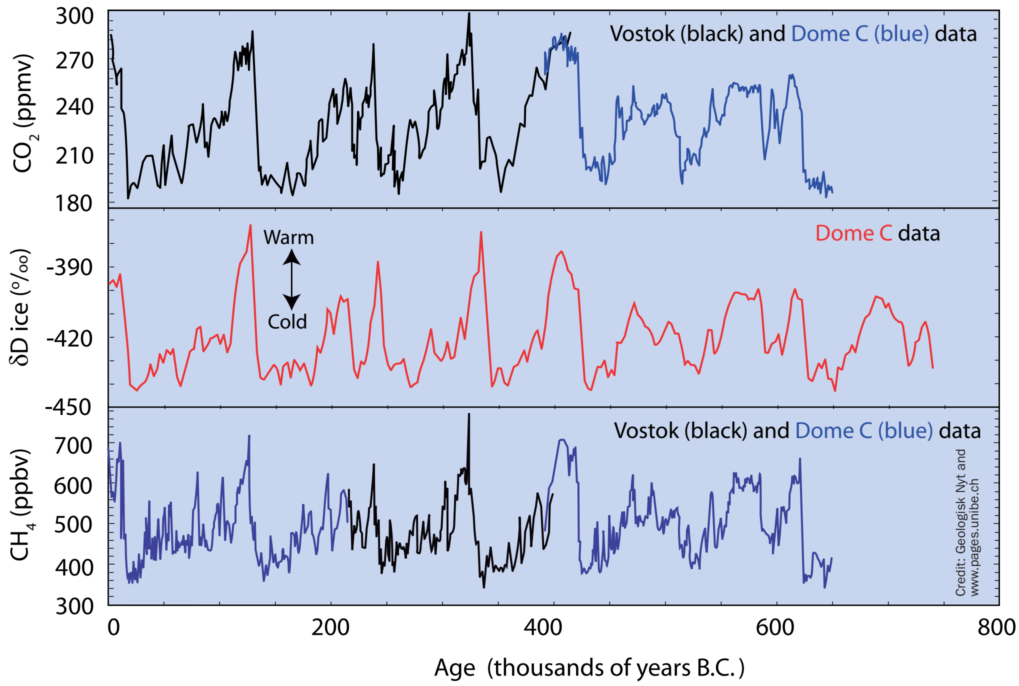
The climate sensitivity term was introduced in order to correlate the temperature increases derived from different types of climate effects. As it turns out, if we only know the numerical values for the change in energy input (called forcing), the initial temperature change will be independent of the reason for the change in energy input.

Climate sensitivity is perhaps the most important of all the climatic parameters, but unfortunately it is not well known. A rough way to estimate climate sensitivity is to calculate the temperature increase required in order for upward infrared radiation to correspond to a specific increase in the power supply. A simple calculation tells that a change in the power supply of 1 W/m^2 gives a sensitivity of 0.269 K / (W/m^2) (see box).

This simple estimate results in far too low a climate sensitivity. In the real world there are a number of so-called feedback mechanisms, whereby a change in temperature causes a change in other parameters, such as the atmospheric water vapor content, which in turn changes the energy balance and thereby causes an additional temperature change. Feedbacks that reinforce a warming or cooling are called positive, while those that suppress them are called negative.

Feedback Mechanisms

Water vapor is a greenhouse gas and increased water vapor content in the atmosphere enhances the greenhouse effect. Water vapor high up in the troposphere gives a particularly strong greenhouse effect, since it is much colder there than on the surface. As a warm atmosphere can hold more water vapor than a cold atmosphere, a warming may increase its water vapor content, enhancing the greenhouse effect, thereby increasing the warming even further. Water vapor feedback is positive. All simulations of future climate (using climate models) include the effect of increasing



Credit: Geologisk Nyt and www.pages.unibe.ch

Data from two Antarctic ice cores. The upper and lower curves show the carbon dioxide and methane concentrations through time (back to 650,000 years before the present date). The middle curve shows δ-Deuterium, which is an indicator of temperature. The three fluctuate synchronously – the temperature tends to rise (or fall) first and then the greenhouse gases follow suit thereby reinforcing the temperature change.

Feedback Mechanisms in the climate system

The climate is a closely interconnected system with a wide range of components, such as temperatures, winds, water vapor, clouds, ice, snow, oceans, vegetation and much more. If the temperature changes, it will lead to changes in other components, which in turn may cause additional temperature change. Thus the playing field has been readied for a host of mutually interacting feedback effects. Some examples are:

Ice and snow cover
Warming will lead to a reduction (by melting) of snow covering the continents and of sea ice. This in turn causes a reduced reflection of sunlight from the Earth's surface and thus creates more warming and additional melting of snow and ice. The ice and snow cover feedback is therefore positive.

Clouds
In total, clouds in the Earth's atmosphere have a cooling effect (≈20 W/m^2), because in spite of their contribution to the greenhouse effect their cooling albedo effect is greater. Clouds are very diverse and occur at different altitudes in the atmosphere. There are both negative and positive feedbacks from clouds, depending on height and type. The total feedback from clouds is uncertain and requires further study.

Water vapor
When the temperature rises, the atmosphere can hold more water vapor, nearly 7% more for each degree the temperature rises. This reinforces the greenhouse effect, and causes additional warming, i.e. a positive feedback.

Temperature-profile
Typically, the temperature changes more rapidly at the radiation level than at surface level, and radiation will quickly adapt to the forcing. On the surface we will therefore only experience a slight change. This is a negative feedback.

Heat transport
The transports of energy in the atmosphere and in oceans can be affected by a changed climate, and this may cause a feedback but further study is necessary to determine if it is positive or negative.

Vegetation
The distribution of vegetation types and their volume may change, and this will affect the albedo. The exchange of water vapor between the surface and atmosphere will typically be affected by vegetation as well. Both effects may be sources of feedback.

CO_2 feedback
We have previously described CO_2 as a forcing factor of the climate system, but on a long time scale CO_2 is actually also a part of the feedback system. For example, the solubility of CO_2 in seawater is reduced in a warmer climate, and the sea will thus serve to reinforce the CO_2-forcing. Further, a number of biological processes in both sea and on land are temperature dependent. These feedbacks can start in two different ways:

1) Glacial fluctuations are believed to start with an astronomical forcing; changing the temperature, which in turn changes the CO_2 concentration. This further strengthens the temperature signal.

2) Anthropogenic CO_2 emissions can cause the temperature to rise, and this then affects the CO_2 concentrations.

Cooling towers by a power plant.

Photo: Colourbox

water vapor through the physical processes which link air temperature and air's ability to contain water vapor.

Climate sensitivity is thus affected by the overall effects of feedback mechanisms. In order to determine it with greater accuracy than can be done with a simple calculation without feedback mechanisms, we utilize detailed climate models which represent physics such as ocean and air currents, radiation, and thermodynamics of the atmosphere, ocean, and land. Observations of climate trends over the last 150 years and reconstructions of climate change on longer time scales (for example, ice ages) are also used to determine sensitivity. With these methods we come to an approximate value of 0.75 K / (W/m^2), and feedbacks thus create more than a doubling of the sensitivity compared to calculations without feedbacks. It is important to note that there are significant differences between sensitivity calculations. Estimates range from about 0.5 to more than 2.

When calculating temperature changes as a result of a change in atmospheric CO_2 content, it is associated with a certain degree of uncertainty. The main contributor to this uncertainty however, comes from sensitivity rather than forcing. The cause for this is that the forcing is reasonably well known (for example, a doubling of CO_2 in the atmosphere will lead to an increased energy input of 3.7 W/m^2), while the different models and different data methods offer great variation in the value of sensitivity. The reason for this variation, as mentioned previously, is that the climate system's feedback mechanisms give a strong increase of sensitivity and the strength of these feedbacks varies from model to model.

This means that regardless of what previously has driven and today keeps driving the climate changes – whether it is greenhouse gases, volcanic activity or astronomical effects – all calculations face the uncertainties derived from the climate sensitivity. This uncertainty is further increased due to uncertainties regarding the forcing, and here the greenhouse effect is the best understood and mapped mechanism.

It should be noted that the geographic pattern of climate change does not follow the geographic pattern of the forcing. Internal dynamics of the climate and local feedback mechanisms cause the increases in temperature resulting from increasing atmospheric carbon dioxide concentration to be greatest in the Polar regions, even if the forcing is more pronounced in the tropics. ■

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Is the ice burning?

The impact of global climate change is commonly illustrated by the media with images of retreating and melting glaciers. But what is the state of the world's glaciers, seen through the eyes of science?

By Kurt H. Kjær

■ The impact of climate change, is often dramatically portrayed by cascades of melt water gushing over the surface of glaciers to thunder off of its edge with large icebergs, or to disappear into deep crevasse in the ice. There is no doubt - the ice burns, while CO_2 is pumped into the atmosphere. The ice will dwindle away year after year on top of the world's mountains, while giant islands of ice tear themselves loose and drift away from the world's large ice sheets in Antarctica and Greenland, revealing never before seen fjords and valleys. According to the media, and opinion makers that is the world we and our children will experience in a time of global climate change. But what is the state of the world's glaciers, why are we so interested in them in a global perspective and do they react unexpectedly to the changing climate?

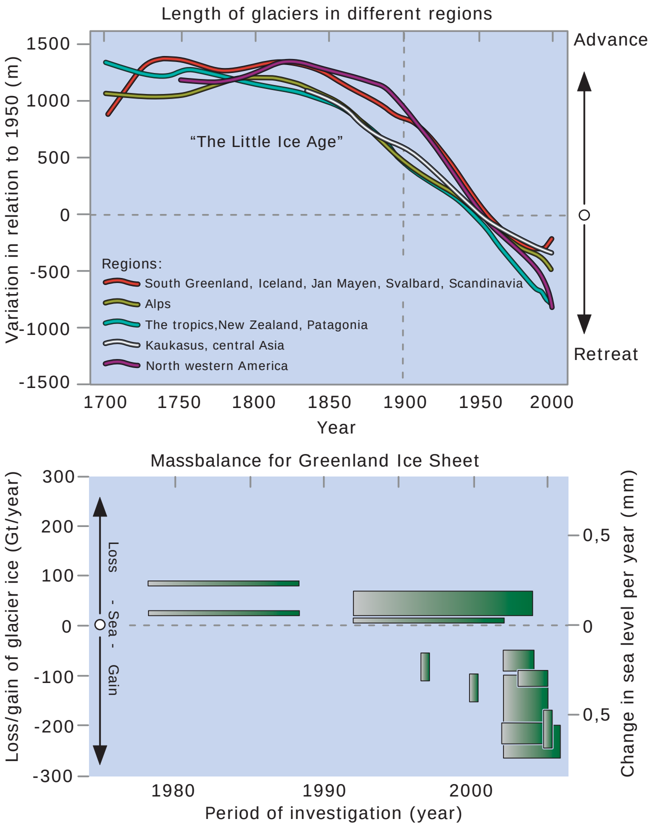


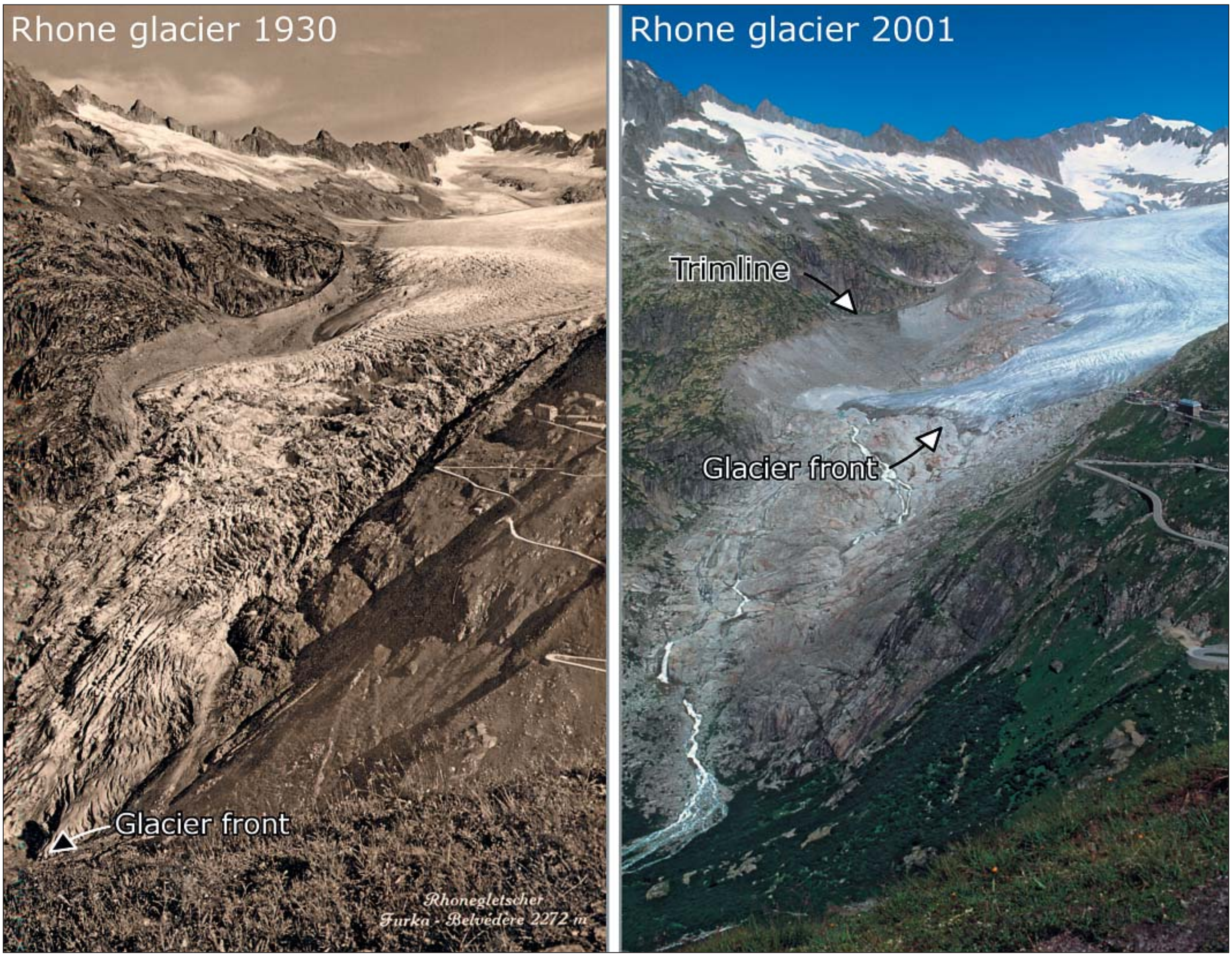
Figure 1. Top: Overview of the state of the world's glaciers during the last 300 years based on the length of glaciers in various regions. The vertical dashed line shows the end of the Little Ice Age.

Bottom: A comparison of decadal mass balance studies from the Greenland ice sheet. The boxes show the uncertainty of the period. Most of the latest studies find a gradually increasing loss that started back in the mid-1990s. *Source: partially after the IPCCs AR4, 2007.*

Melting

The ominous predictions are to a large extent due to projections of the developments that have occurred within the last few decades. The evidence of which has been provided to us by new advanced aircraft and satellite monitoring, revealing the yearly development of glaciers in frozen regions. Since the early 1980s mass balance measurements have been done across the Greenland ice sheet that calculate the loss or growth of glacier ice each year (Figure 1). These measurements indicate that within the last 15 years the overall loss of glacier ice is approximately 50-230 gigatons per year, and while the central areas of the ice sheet are growing slightly in thickness, the ice in coastal areas is thinning at an even faster rate. The mass of the Antarctic ice sheets is also changing by somewhere between +50 to -200 gigatons of glacier ice per year, but the uncertainty is of the same magnitude as the variation and changes over the last 10 years seem to be more modest than in Greenland. The total result represents a patchy collection of data from different methods and analyzed in different ways. This is because of the difficulties in collecting comprehensive datasets, so most of the investigations carried out have limited coverage over the ice sheets and the result must be extrapolated from a small study area for the entire mass of the ice, in order to provide an overall picture. That different survey methods yield different results is hardly surprising, when you take the huge areas of the ice sheets into account, but together with the short time interval of the investigations it does make it difficult to assess the stability of ice sheets in Greenland and Antarctica, when the natural variation cannot be discerned from the actual observed changes. Within this context it is interesting to look further back in time - some 9000 - 6000 years ago, when the climate in Greenland was similar to or perhaps slightly warmer than it is today and the edge of the Greenland ice cap was in several places 20 kilometer farther inland than its current position.

By studying historic paintings and photographs, we can verify



Credit: Sammlung Gesellschaft für ökologische Forschung, München

Figure 2. The Rhône Glacier in Switzerland - past and present. The sharp change in color on the mountain side shows where the glacier surface was during the Little Ice Age, in the period between the years 1500-1900. The glacier has had an overall negative mass balance since the end of the Little Ice Age.

that the volume of smaller glaciers has also changed in the past. During the Little Ice Age between year 1500 - 1900 AD, when the climate was colder, most of the world's glaciers grew and stopped several times in an advanced position (Figure 2). Also in the Alps, we can track the melting since the Little Ice Age and see how the length of glaciers was reduced year after year (Figure 1). Glaciers are thus sensitive and reliable indicators of climate change, and they adapt to and achieve balance when their size match the surrounding climate. The trend from the Alps can be recognized in most other valley glaciers around the world. The present change in glacier frontal position is not just an extension of the withdrawal at the end of the Little Ice Age as many of these glaciers stopped their retreat or even advanced from 1950 to 1975, in response to a slightly cooler period in the 1940s. The present melting must therefore be coupled to the last 30 years of climate development. On the Antarctic Peninsula, a new survey shows that nine tenths of the glaciers there have retreated over the past half century.

But the story is even more interesting because it is not only the warming of the atmosphere, which causes changes in the glaciers' mass. The very symbol of global climate change – the Kibo Glacier atop Kilimanjaro in East Africa – is apparently not affected by atmospheric warming, since the entire glacier is still far below the freezing line. At an altitude of 5000 meters, the temperature is around 32 °C colder than at sea level. Instead scarce precipitation in the form of snow appears to be starving the glacier, while at the same time it is losing mass by sublimation, which is when ice changes phase directly to water vapor because of strong solar radiation. The trend may be linked to a centuries-old change in the atmospheric circulation and precipitation patterns in the Indian Ocean. If global warming plays a role, it must be as an enhancer of a longer-term development and not the only cause of the disappearance of "the snows of Kilimanjaro".

The global attention

The main interest in the state of the world's glaciers and the large ice sheets on Greenland and Antarctica is focused on their impact on oceanic sea levels and changes to water circulation in the North Atlantic. The relatively small glaciers that are typically found in the Scandinavian and North American mountains, as well as the Alps or the Himalayas, are without great global significance. However, their melting may have a significant impact on regional water resources and climate conditions. In the Himalayas melt water stored in large ice lakes can

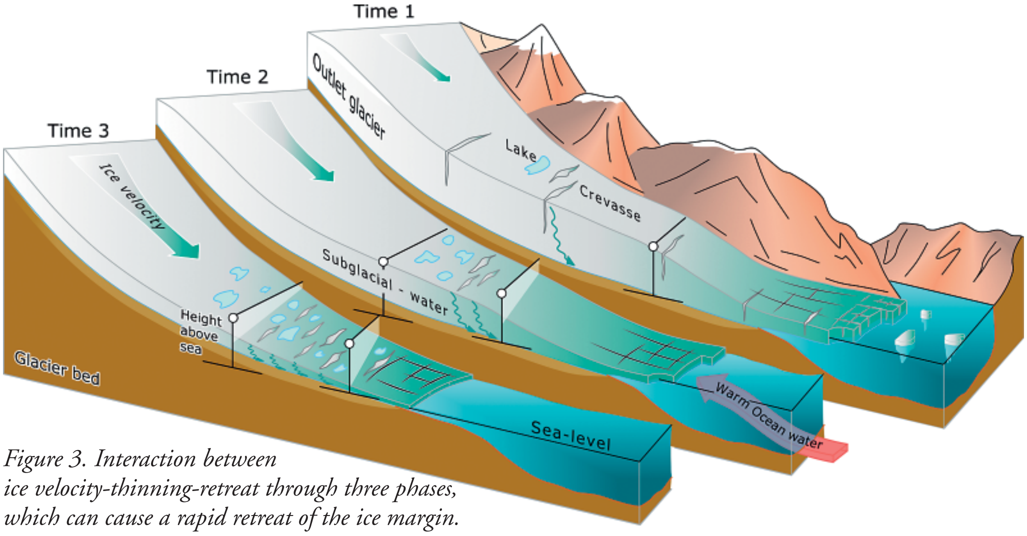


Figure 3. Interaction between ice velocity-thinning-retreat through three phases, which can cause a rapid retreat of the ice margin.

suddenly be drained, with disastrous consequences for the local population living in low-lying valleys.

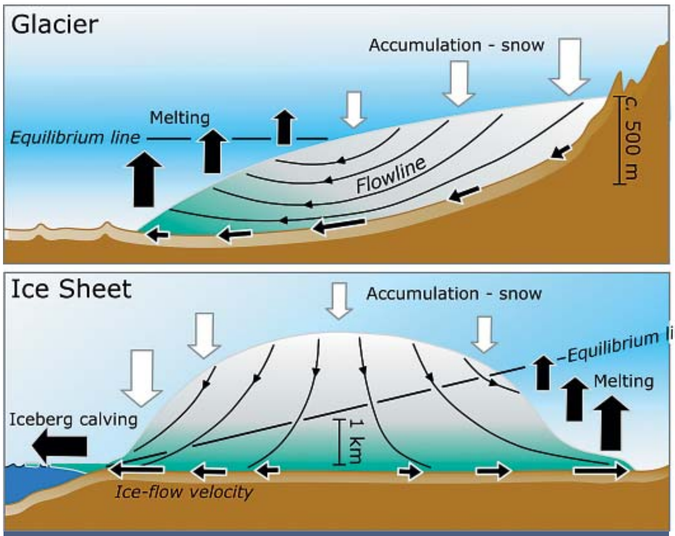
On a global scale, it is the Greenland ice sheet and ice sheets in Antarctica that can fundamentally affect Earth's climate system. A melting of the entire Greenland ice sheet would lead to a global sea level rise of 7 m, and if the Antarctic ice sheets all disappeared it would lead to a further increase of 50-60 m. The loss of mass from the Greenland ice sheet at the moment is equal to sea level rise in the oceans of up to 0.8 mm per year (Figure 1). But even a moderate sea level rise of less than 1 m will have serious consequences for low-lying coastal areas of economic importance. Huge amounts of fresh, cold melt water could change present ocean currents, which would inevitably change the climate in the countries around the North Atlantic. Climate changes normally only affect the large ice sheets after a certain period of time - the so-called response time. The Greenland ice sheet is expected to respond to climate changes over a period of several millennia, and a contribution of several meters to the global sea level rise in the foreseeable future is unlikely, although models suggest that, under current conditions, around a meter of sea level rise is expected by the end of the century from melting of the Greenland ice sheet alone. But predictions such as this depend on our understanding of the processes controlling the stability of the ice sheet.

It can quickly happen

A very surprising discovery of recent research is how quickly outlet glaciers from the inner part of the Greenland ice cap can change speed. Two of the big outlet glaciers in South-Greenland – Helheim and Kangerdlugssuaq doubled their speed in one year (around 2004) only to return to their initial speed two years later. The acceleration was so powerful that a number of smaller earthquakes triggered at the bottom of the ice could be registered as it quickly slid across the bedrock. These events showed one thing with certainty: We do not understand the dynamics behind these changes and their connection to climate.

The Antarctic ice also seems to respond more dynamically than expected. Over large areas the East and West Antarctic ice sheets are surrounded by floating glaciers known as ice shelves. Several times during the last 10 years huge ice shelves have broken off, and islands of ice the size of Fyn Island, Denmark (over 1000 sq. miles) have drifted away. The problem is not the floating ice in itself as it does not contribute to extra sea level rise, but rather that the outlet glaciers in the valleys behind are no longer held back by the ice shelf. The valleys are therefore drained of ice incredibly fast and more ice is pulled out to the sea from the inner part of the ice sheet. This does contribute to a rise in sea level and may also suggest that further collapse of ice shelves could put the ice sheet at risk of collapse.

Although the largest ice masses of the Greenland ice sheet are found in the interior, it is the local climatic conditions and drainage in the periphery, which determine how fast the ice responds to climate changes. It has also been discovered that melt from the ice surface can find its way to the bottom of the ice more quickly than was expected. In some areas, this creates a thin meltwater layer, which lubricates



Climate Balance

– glaciers and ice caps

The size of valley glaciers and ice sheets is the product of the balance of the annual precipitation, that is snow accumulating on the glacier surface, and the annual loss of mass, which can be attributed to ice calving (icebergs), surface and bottom melting and in very cold climates, sublimation. In warmer climates and regions with less snowfall this mass balance becomes negative, and the glacier front retreats. However, if the climate becomes colder and/or snowfall increases the mass balance is positive and the glacier will advance. Usually, most snow falls in winter and more ice and snow melts in summer. The point at which the winter snow fall does not melt during summer, and where the snow does melts away completely is called *the equilibrium line.*

Above the equilibrium line, in the accumulation zone, snow is transformed into ice that slowly flows toward the bottom of the glacier and out toward the margin forced by gravity. A healthy glacier has slightly more than half of its area above the equilibrium line. If this is not the case the glacier will adapt to the new situation, but if the equilibrium line is very high or entirely above the glacier, no snow is accumulated on its surface and the melting becomes dominant.

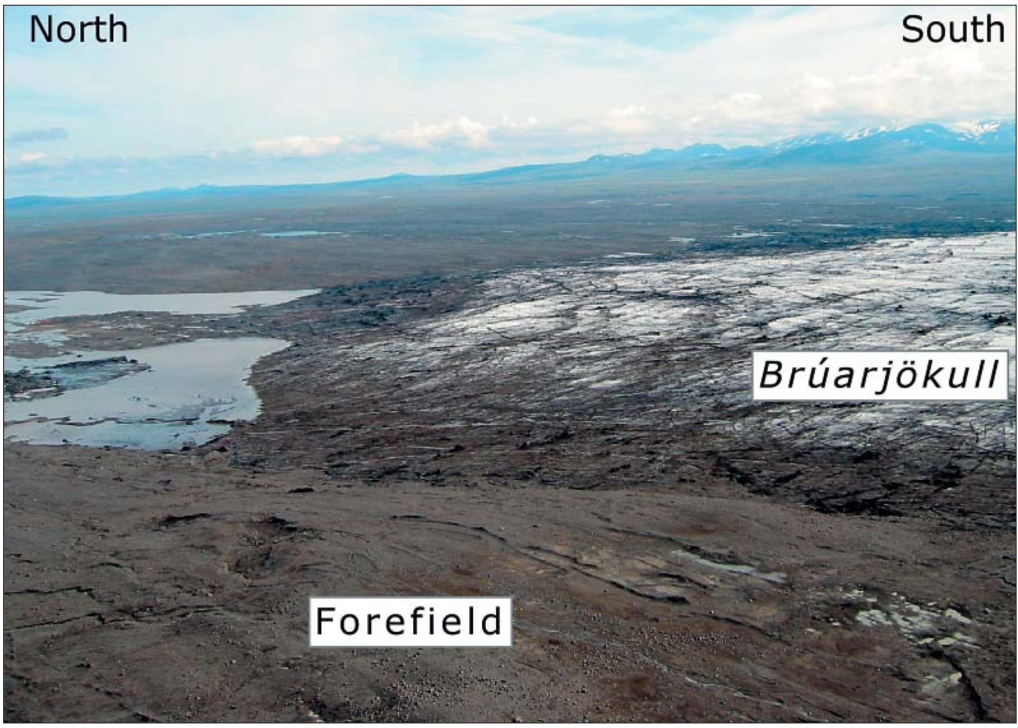
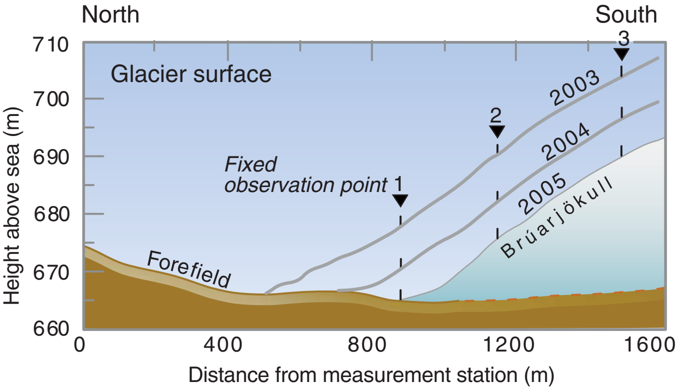


Photo: Kurt H. Kjær

Figure 4. Northern margin of Vatnajökull in eastern Iceland, summer 2003, seen from a helicopter over glacier. Brúarjökull – an outlet glacier of Vatnajökull surged 8 km during the winter of 1963/64 and is now rapidly melting again. Under the current climate the glacier fronts withdraw by up to 200 meters (600 ft.) per year – a perfectly natural situation, because the glacier ice has been brought down in an area with a climate which normally does not permit glaciers to exist.

the glacier bed and significantly enhances acceleration. This initiate a dynamic process: the acceleration depletes the ice reservoir and the surface loses elevation and is thus exposed to higher temperatures, which in turn leads to increased melting - more melt and even higher speeds (Figure 3). The outlet glacier will during this interaction move back periodically as dictated by the topography. The dynamic processes could potentially shorten significantly the response time to the changing climate of the Greenland Ice Sheet. Lately is has been documented that the penetration of warm subsurface waters to the margin of the Greenland ice sheet triggers a rapid dynamic response.



The melting of Brúarjökull from 2003 to 2005.

The unsuitable

In the climate debate before-and-after photos of glaciers, which have changed their size considerably over the past 100 years (Figure 2), are often shown as evidence. But in several cases the type of glaciers chosen are not suited for this kind of simplistic representations. These are the so-called surging glaciers that suddenly advance several kilometers in the course of weeks or months and then rapidly melt back (Figure 4). The cycle of rapid advance and slow retreat is partially a response to climate, but is mainly a result of internal processes in the glacier. By highlighting the melting phase only half of the truth is told, namely that glacier ice is transported disproportionately far and placed out of balance and quite naturally melts again to adjust to the surrounding climate.

It is clear that almost all the world's glaciers and large ice sheets are out of balance with today's climate. Most melt back, while other receives more snowfall as a product of warmer and more humid weather. The later maintain their current position for the time being. The time scale of our experience with these rapid changes is not great and only future monitoring and reconstruction of earlier development dating thousands of years back in time can put them in the right perspective. ■

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Further Reading:

The Intergovernmental Panel on Climate Change (IPCC), Chapter 4: Observations: Changes in Snow, Ice and Frozen Ground.http: / / ipcc-wg1. ucar.edu/wg1/wg1-report.html

Das Gletscherarchiv. Glacier Archives from the Alps with comparative photographs from the end of the Little Ice Age and now. www.gletscherarchiv.de

World Glacier Inventory. "The World Glacier Inventory contains information from more than 67,000 glaciers around the world. www.nsidc.org/data/g01130.html

International Exhibition on Climate Change in the Botanic Garden http://snm.ku.dk/english/udstillinger/climateexhibit/

Is 'Tipping Point' for the Greenland Ice Sheet approaching?

Once an ice sheet starts to have continuously negative surface mass balance, the ice surface gradually decreases in altitude and become warmer, leading to more melting in a positive feedback effect.

By Sebastian H. Mernild

■ Observations indicate that the most pronounced temperature increase occurs at higher northern latitudes, which have increased at almost twice the global average rate in the past 100 years. Since 1957, air temperature for the Arctic has increased on average more than 2°C. The warming was accompanied by an average increase in precipitation of ~1% per decade.

The Greenland Ice Sheet is the Northern Hemisphere's largest terrestrial permanent ice- and snow-covered area and represents a reservoir of water, containing between 7.0 and 7.4 m global sea level equivalent. This ice sheet is a useful indicator of ongoing climatic variations and changes, and it is suggested that the ice sheet responds more quickly to climate perturbations than previously thought. It is therefore essential to predict and assess the impact of future climate on the ice sheet. Variability in mass balance of the Greenland Ice Sheet closely follows climate fluctuations; the mass balance was close to equilibrium during the relatively cold 1970s and 1980s, and lost mass rapidly as climate warmed in the 1990s and 2000s with no indication of deceleration. A response to the altered climate has already been observed, manifested by a retreating ice sheet, increasing surface melt extent, decreasing permanent snow cover, and increasing freshwater runoff to the ocean.

Photo H. H. Thomsen, GEUS

The Greenland Ice Sheet 65 km north of Kangerlussuaq, W. Greenland.

Contributing to sea level

Recent research studies have shown that the present annual ice sheet mass loss is around 250 km^3, where nearly half of the loss originates from surface melting and subsequent freshwater runoff, and the other half from iceberg calving and geothermal melting. The mass loss affects the freshwater flux both to the West: Baffin Bay, Davis Strait, and Labrador Sea and to the East: Greenland–Iceland–Norwegian Seas. The freshwater flux plays an important role in determining ocean salinity, thermohaline circulation, sea ice dynamics, and the global sea-level rise. At local scale the freshwater increases the potential for hydro power in Greenland. At present the mass loss is equivalent to a net global sea-level rise of approximately 0.7 mm per year, or 25% of the global sea-level rise of approximately 3 mm per year.

Tipping point in the 2040s

A highly sophisticated surface snow, ice, runoff, and energy balance model (SnowModel), was used to simulate the Greenland Ice Sheet surface mass balance, and the surface freshwater flux to the ocean from 1950 through 2080. The simulations were based on input data from the Intergovernmental Panel on Climate Change (IPCC) scenario A1B modeled in a high resolution Regional Climate Model (HIRHAM4).

The projected climate data (1950–2080), air temperature and precipitation are shown in Figure 2. The greatest changes in mean annual air temperature of 5.6ºC occurs in NE Greenland; this is likely due to the projected change in sea ice extent off the east coast of Greenland. The lowest warming, 3.6ºC, occurs in SW Greenland, where sea surface temperatures are changing only slightly. Overall, the temperature is projected to increase by 4.8ºC. Precipitation was found to increase by 80 mm on the ice sheet, with the lowest gain of 57 mm in NW Greenland and the greatest increase of 160 mm in SE Greenland, due to projected changes in cyclonic systems. The overall trend for the predicted climate (1950–2080) is a warmer and wetter climate.

The projected change in climate for Greenland will lead to an enhanced average ice sheet loss and runoff in the years approaching 2080. The annual surface mass balance changed from positive to negative values, displaying that continuously negative mass balance values will occur from the beginning of the 2040s. As the ice sheet also will continue to lose mass, partly through the dynamic production of calving icebergs, for example at Jakobshavn in West Greenland, and at Helheim in East Greenland, and partly by geothermal melting and by melting at the interface between glacier ice and warmer ocean water, the ice will have no way to recover its volume, as long as the surface mass balance continues to be negative. Once an ice sheet has continuously negative surface mass balance, the surface gradually decreases in altitude and warms up, leading to further melting in a positive feedback loop. When this irreversible process takes over, the 'Tipping point' for the Greenland Ice Sheet has been exceeded.

A global rise of only 0.6°C can cause tipping point

The climate model used in SnowModel predicts that the tipping point for the Greenland Ice Sheet will be exceeded in the early 2040s following a warming of 1.2°C, compared to present temperatures. It is most realistic to assume that the early 2040s is the latest that tipping point may occur, since observations have in general evolved faster than the IPCC climate model scenarios. As the temperature increase in the Arctic, including Greenland, on average, probably will continue to be twice the global average rate, there is a reason to expect that the tipping point may be reached at a global average temperature increase of approximately 0.6°C. This is low, compared to temperature predictions based on simple climate models, like the positive degree day model. These degree day models predict that the tipping point will be reached at a global temperature increase of 3°C. The choice of model concept and framework conditions can obviously be important. The HIRHAM4-SnowModel concept is far more physically realistic than the degree day approach. Therefore, it seems more reasonable to expect the tipping point to be reached at a global temperature increase of 0.6°C, rather than an increase of 3°C from today's average global temperatures.

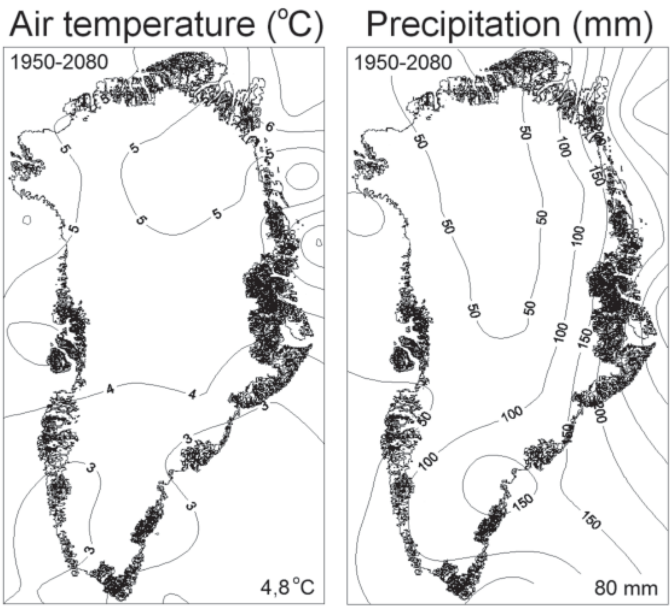

Figure 1: Greenland HIRHAM4 RCM average annual difference from 1950 through 2080 for the parameters air temperature and precipitation.

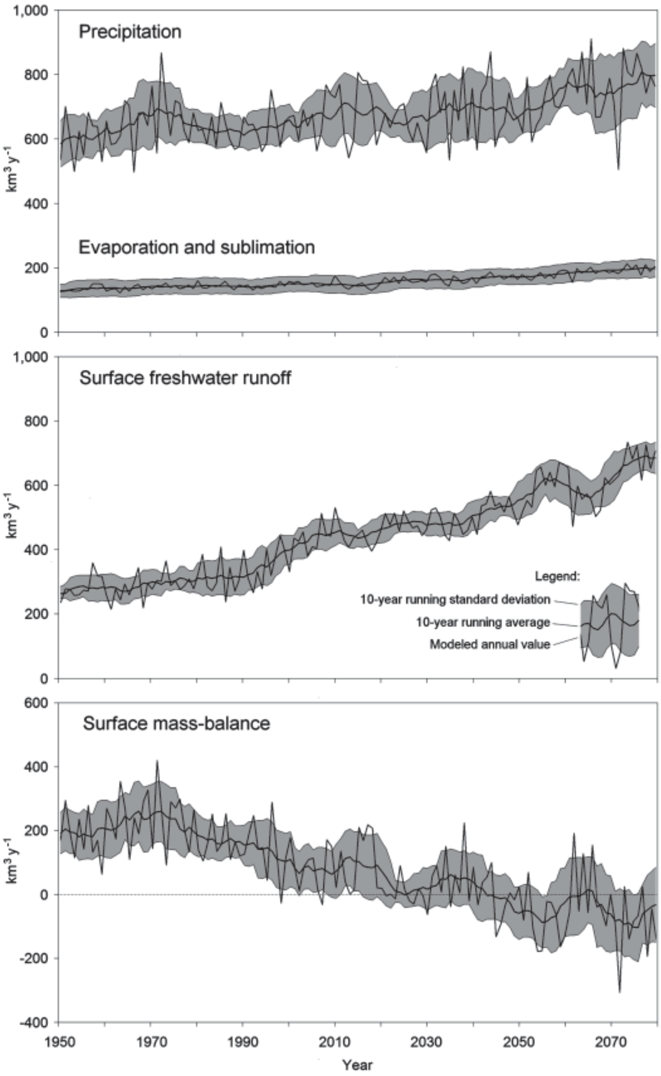

Figure 2: Time series for the simulated Greenland Ice Sheet precipitation, evaporation and sublimation, surface freshwater runoff, and surface mass-balance for the period 1950–2080.

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Thanks to the Danish Climate Center, Danish Meteorological Institute, for the use of the Regional Climate Model HIRHAM4.

Further Reading:

Definition of tipping point:
Bamber, J. and others 2009. What is the tipping point for the Greenland Ice Sheet? IOP Conf. Ser.: Earth Environ. Sci. 6 062007, Pp 1. DOI: 10.1088/1755-1307/6/6/062007.

SnowModel used on the Greenland Ice Sheet:
Mernild, S. H. and others 2009. Greenland Ice Sheet surface mass-balance modeling in a 131-year perspective 1950–2080. In press Journal of Hydrometeorology.

Mernild, S. H. and others 2009. Greenland Ice Sheet surface mass-balance modeling and fresh water flux for 2007, and in a 1995–2007 perspective. Hydrological Processes, DOI: 10.1002/hyp.7354.

HIRHAM4 Regional Climate Model: Stendel, M. and others 2008. Arctic Climate and Climate Change with a Focus on Greenland, Adv. in Eco. Res., 40, 13–43, DOI: 10.1016/S0065-2504(07)00002-5.

The frozen sea

Photo: Peter Bondo

The extent of sea ice at the North Pole diminishes by an area equivalent to that of Denmark (almost 17000 sq. miles) each year. This is to a large extent due to global warming, but natural variations in current systems in the Atlantic also have a vital role.

By Torben Schmith and Rasmus Tonboe

■ One hundred years ago, in 1909, Robert Edwin Peary reached the North Pole. Before him, several other daredevils had in vain tried to be the first men to set foot there, but the Arctic Ocean ice was hard to cross. The ice is not a plane surface - the wind and the movement of the water open cracks in the ice, where new ice is formed, while ridges and fissures are formed in other places. These conditions make it difficult and dangerous to navigate the ice.

Since Peary's feat, the interest for the Arctic Ocean has not lessened - although it today does not have the same spirit of adventure and exploration. The extent of sea ice is carefully studied, because it is expected to be in the Arctic, that is around the North Pole, where climate change will be strongest felt.

At the North Pole, some 15 million km^2 of ocean are covered by ice, when winter is at its highest in March, while the corresponding figure in Antarctica is around 20 million km^2 in the winter in September. Sea ice is on average 3-4 meters thick (see box).

Will there be less ice?

We know from satellite data that the extent of sea ice in the Arctic has seen a steady decrease since the late 1970s. The extent of sea ice during winter has decreased by 10% from 16.4 million km^2 in 1979 to 14.8 in 2005 while the area covered by sea ice during summer has fallen by 25%, from 7.2 million km^2 in 1979 to 5.6 million in 2005.

The extent of ice in the Arctic Ocean is significantly below the average for the 1979-2000 period. Early satellite data from 1972 show that sea ice actually increased in the mid 70s until 1978, after which the reduction began. The reduction has accelerated over the past years – for example, sea ice was reduced from 1987 to 2004 by 32,700 km^2/year but in the period 1991 to 2004 the extent of sea ice was reduced by 46,900 km^2/year, approximately the equivalent to Denmark's land area each year.

The reductions of sea ice seen in recent years surpass even the most pessimistic model scenarios. In early September of 2007 the extent of sea ice was the lowest ever recorded, coming under 3 million km^2!

The short explanation is that rising levels of greenhouse gases in the atmosphere raise the temperature at the sea's surface, and the ice reacts to that by melting faster and at higher latitudes than previously.

However, a contributing factor is that, since our data comes from satellites, accurate data on the extent of sea ice covers a very short period of time. This means that our first series of measurement start in 1972, and 37 years is generally considered a very short time in climatological terms. We cannot yet be certain that global warming is the whole reason for the meting, but there is certainly circumstantial evidence.

There is however, an interesting point to be made about the Arctic. It was very warm there in the 1940s. In fact, the temperature was on a par with current observations. Research at DMI has previously shown that the 1940s in particular were characterized by a reduced level of ice along the Greenland east coast compared to the decades before, just as we experience today. We are therefore presently endeavoring to identify what the causes of warming in the 1940s were, but it may be explained by the natural variations of the Atlantic current system, known as the Atlantic multidecadal oscillation (see the box on next page).

The role of sea ice in the climate system

Ice has a high albedo, which means that because ice is white it better reflects incoming energy in the form of solar radiation. If the ice melts away completely, the underlying and much darker seawater, which absorbs much more solar radiation, will be exposed, heating the atmosphere. Thus, reduced ice cover leads to higher temperatures, which in return lead to even less ice cover. Sea ice therefore represents a negative or destabilizing feedback, the so-called ice-albedo feedback, which is compensated for by the other feedbacks in the climate system. But due to the ice-albedo feedback, sea ice is an important factor for how much the global climate system changes, when the system is affected by large emissions of greenhouse gases, such as carbon dioxide. This makes it important to understand the magnitude of the ice-albedo feedback when trying to ascertain the future climate with increased volumes of atmospheric carbon dioxide.

Aside from its reflective properties, sea ice also represents a significant quantity of fresh water. Since the temperature on Earth has risen (and is expected to keep rising) it is to be expected that this quantity of sea ice will melt within the next 50 years, meaning that the Arctic Ocean will be ice free dur-

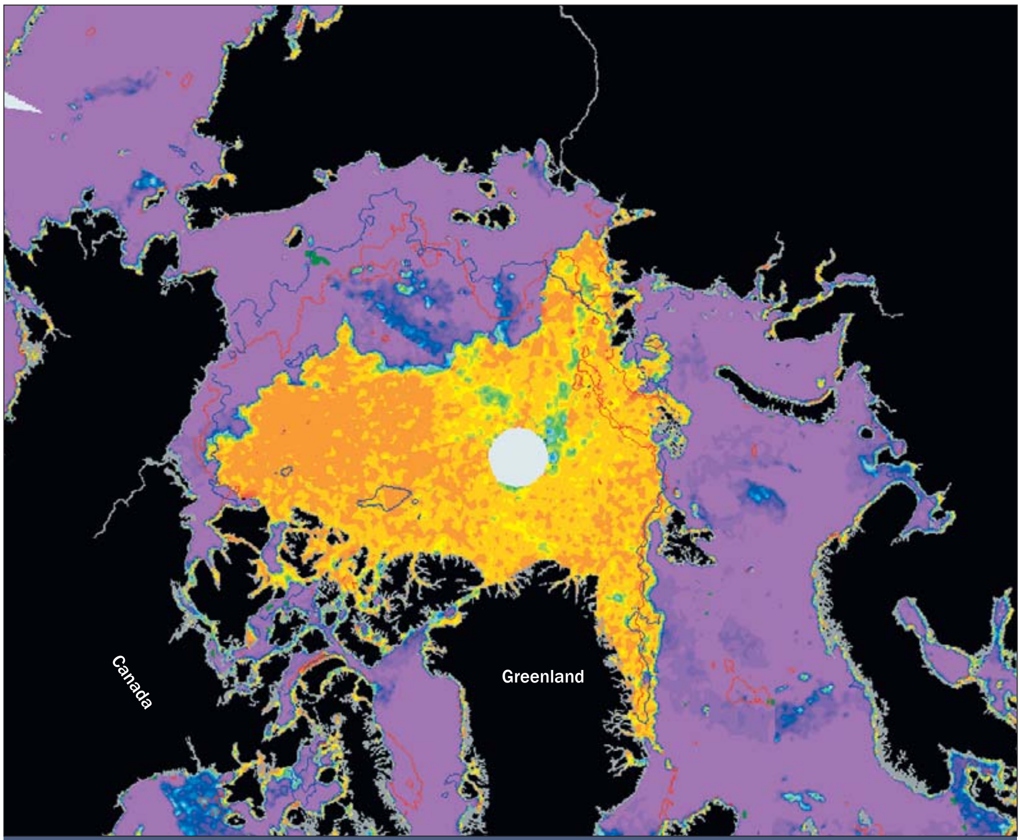


Photo: © www.seaice.dk

The image shows the extent of Arctic sea ice at the summer minimum on August 29th 2007, charted with the American radar satellite QuikSCAT SeaWind. The sea ice extent of August 29th 2006 is indicated by the blue line and the extent of August 2005 29th is indicated in red for comparison. There are yearly relatively large regional variations. 2007 is characterized by an extremely low extent of sea ice in the Arctic Ocean, even if there is slightly more ice along the Greenland east coast than there was in preceding years.

The extent of sea ice

In the Arctic Ocean the smallest extent of sea ice is approximately 8 million km^2 during the late summer (September), while the maximum extent reached in late winter (March) is about 15 million km^2 . The extent in winter is partly limited by the landmasses surrounding the Arctic Ocean. Much of the ice in the central Arctic can survive the summer melting. It can survive five to six summers. Then the sea current carries it south out of the Polar Sea along the east coast of Greenland, where it melts.

The Siberian shelf region is covered by winter ice which either runs towards the central Arctic, where the thickest parts survive, or melts during the summer.

Sea ice can also be found in the southern hemisphere around Antarctica. The summer extent is at its minimum in February (some 4 million km^2) and the winter extent peaks in September with approximately 20 million km^2.

Once the sea is covered with ice the ice continues its growth on the bottom of the floating ice, but a substantial part of the ice volume is found in pack ice. The average thickness of the ice depends on both processes. The average ice thickness in the Arctic Ocean is about 4 meters in March and about 3 meters in September. The thickest ice is found north of Greenland, in the Lincoln Sea and is 5 to 7.5 meters thick.

Photo: © DAMOCLES

The expeditionary vessel, Tara, drifted in the Arctic ice since freezing in October 2006 and passed over the North Pole to the Fram Strait as part of the DAMOCLES project. During the expedition it carried out measurements of atmosphere, ice and sea.

ing summers. Combined with expectations of increased precipitation over the Arctic and the increased melting of the Greenland ice sheet, this will cause a lower salt concentration in the surface of the North Atlantic, which already has been observed in hydrographic profiles. It is feared that this freshening could affect the thermohaline circulation in the North Atlantic. The thermohaline circulation is powered by the cooling of water in the North Sea between Norway and Greenland. This cooling produces more dense water, which sinks to great depth and makes way for warm salty water coming from the south. This circulation is responsible for the relatively warm climate of Western Europe. If the surface water becomes less salty, which as mentioned earlier, has already been observed, it will not readily sink and thus the thermohaline circulation will be hampered. However, experiments with ocean and climate models, performed at DMI, show that these changes are relatively small, and indications are that a sudden change is unlikely.

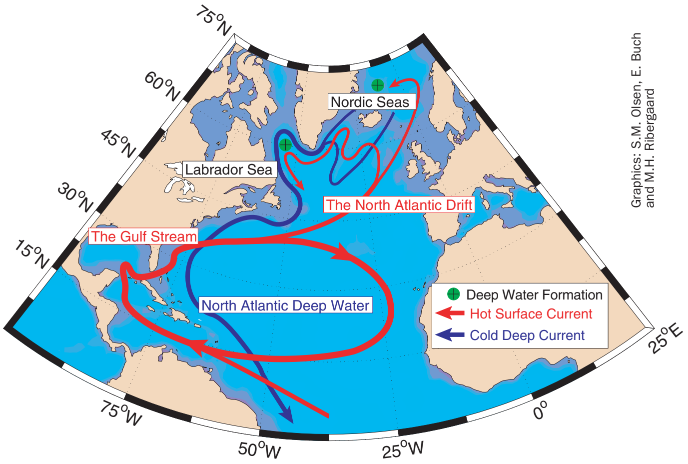
Ice and climate variations

A significant part of the sea ice formed in the Arctic Ocean drifts through the Fram Strait (between East Greenland and Svalbard) and with the East Greenland Current moves along the coast of East Greenland, around Cape Farewell and sometimes along the southwest coast of Greenland. At this stage the ice is known as Storis and can cause problems for maritime traffic in the spring and summer months. Researchers at the DMI have made studies of historical records and observations of this Storis and have been able to reconstruct the ice drift through the Fram Strait. They were able to conclude that there is a significant variability. Thus, the ice drift was relatively modest in the 1940s, which coincided with a warm period in the Arctic. Around 1970 there was much greater drift, but that has since declined once more. It would appear that the ice drift varies

Variation in ice drift and sea currents

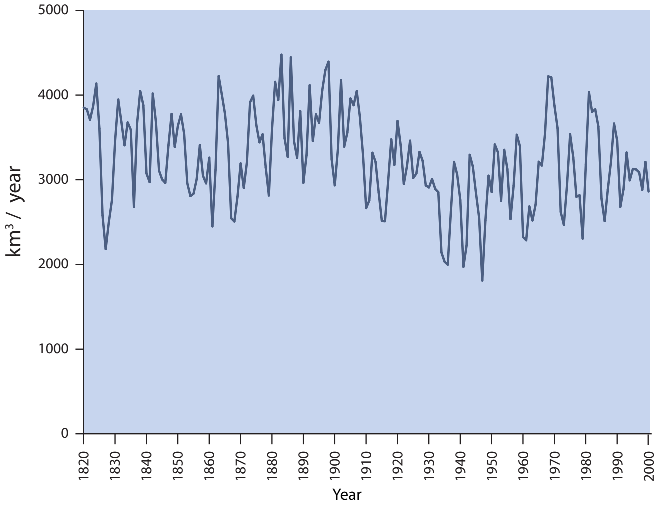
The Atlantic has a sea current system consisting of a northbound warm ocean current, which slowly cools and sinks deep into the Greenland waters, and returns as a southbound current. This is why we in Northwestern Europe, have a relatively mild climate.

But the strength of this ocean current varies. Thus, it was weak in the 1970s, while it was strong in the 1940s, and if we dig deeper into the past we will see that this pattern continues. The amount of ice drifting from the Arctic Ocean into the East Greenland current, varies along with variations in the thermohaline circulation. These variations are called AMO (the Atlantic Multidecadal Oscillation).



Graphics: S.M. Olsen, E. Buch and M.H. Ribergaard

IIllustration of the thermohaline circulation, characteristic of the North Atlantic. Circulation is powered by the cooling of water in the North Sea between Norway and Greenland.



Reconstruction of ice drift through the Fram Strait in the years 1820 to 2000. There is significant interannual variability.

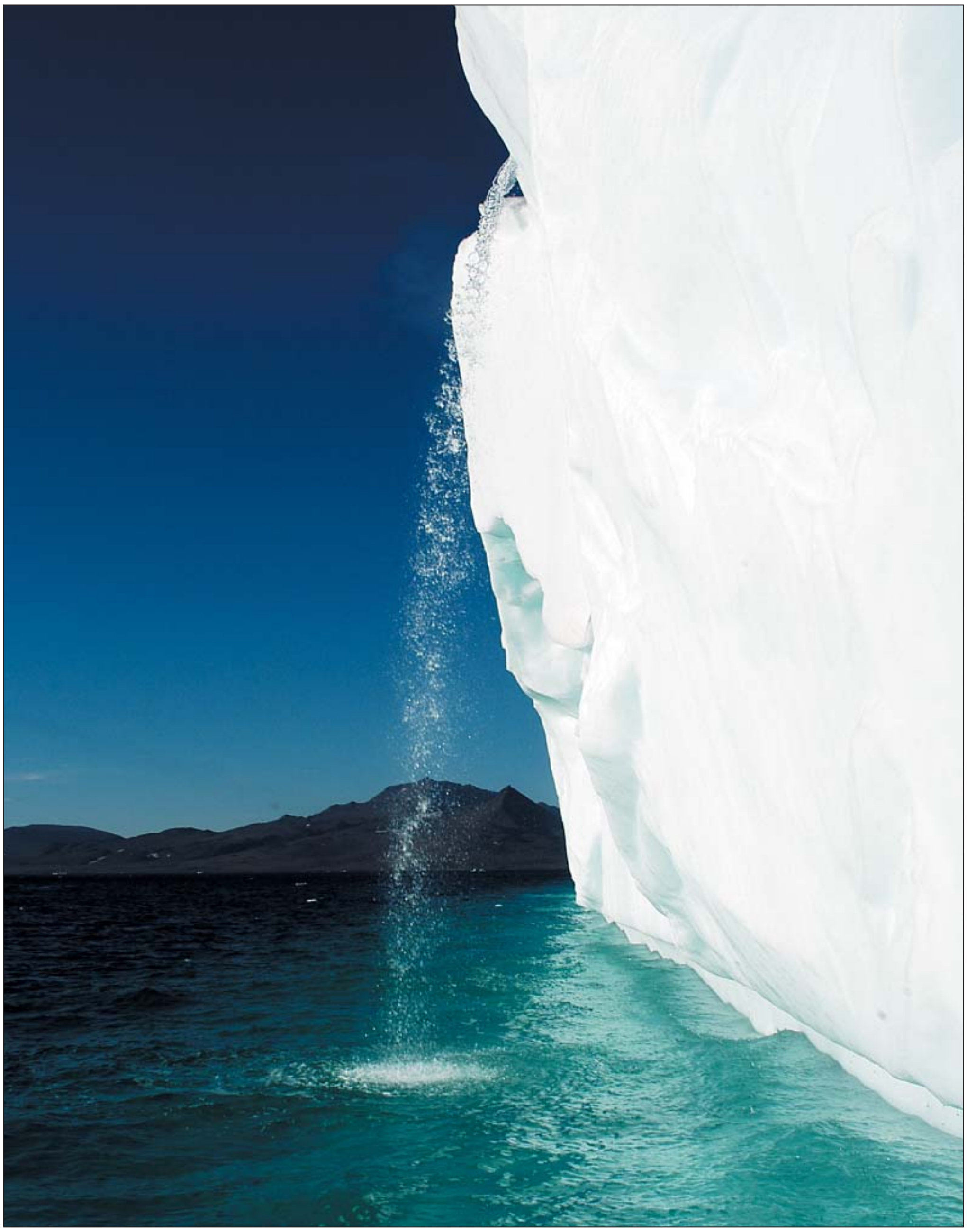


Photo: Peter Bondo

Melting glaciers such as this one can be a great nuisance to shipping.

with a timescale of 50-100 years, which could be linked to corresponding variations in the thermohaline circulation (the aforementioned Atlantic Multidecadal Oscillation). The previously mentioned reduction of sea ice observed from satellites since the 1970s could therefore in part be attributed to a downward phase of a natural cycle.

Heading for an ice-free Arctic?

While there is consensus that the Arctic Ocean ice shrinks with rising temperatures, there is still disagreement as to the degree of the reduction. According to most climate models, the Arctic will largely be ice-free by the end of this century and if the observed trend continues it might happen in the next 20 years. It could have great significance for the shipping, oil and gas industries among others but the price will also be very steep as far as the environment is concerned, with the loss of many animal species and irreplaceable natural amenities.

However, the melted sea ice will not cause the global sea level to rise. Just as a ship, the ice "sails" on the water and displaces a volume of water equal to its weight – the ice's volume in the water is simply replaced by water from the melted ice. With regard to the global sea level the melting of land based ice sheets in Antarctica and Greenland represents the actual threat. A melting of these much larger volumes of ice will occur over a much longer time scale (thousands of years) compared to the melting of sea ice. ■

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Further Reading:
Polar View:
www.seaice.dk og
www.polarview.org

The Damoclesproject:
www.damocles-eu.org

The climate scientists' crystal ball

Credible predictions of future climate depend on climate models that simulate past and present climate convincingly.

Photo: EUMETSAT, Meteosat-8.

By Bo Christiansen

■ Weather and climate are two sides of the same coin, since climate can be defined as the average weather over a long time scale. To describe the weather at a given point in the atmosphere is quite simple – it only requires knowledge of temperature, pressure, humidity and wind direction. However, it is considerably harder to *predict* the weather. Despite the fact that great efforts have been made, throughout history, to make accurate weather forecasts and that today we have numerous data from monitoring stations, and enormous processing power at our disposal, it is still not possible to make reliable weather forecasts that reach more than a week into the future.

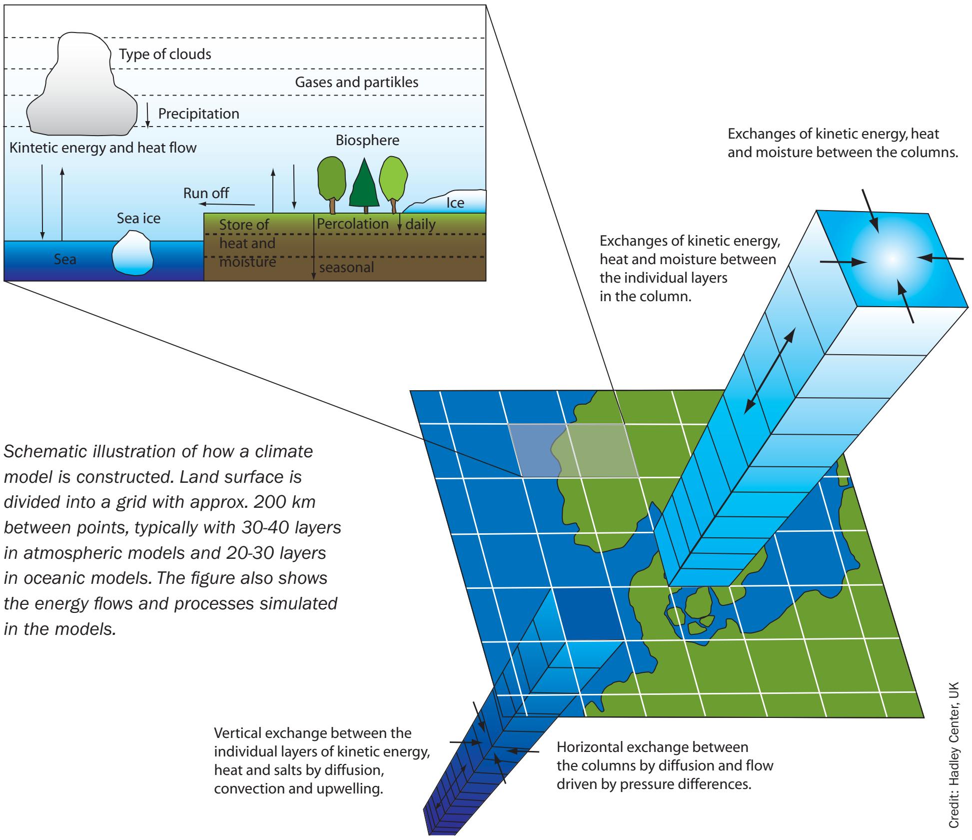
To predict the development of the climate does not differ fundamentally from the daily work with weather forecasts. When you talk about predicting future climate it is obviously not the weather at any particular time in the future, we are interested in predicting, but rather the statistical parameters of average weather conditions and variations around this average. Regardless of whether you want to predict the weather in the coming days or the climate 100 years from now the central requirement is knowledge of the circulation in the atmosphere and ocean. This knowledge is converted into models that simulate this circulation. Thus, climate models become very important to the interpretation of future climate development and thereby also constitute the technical basis for the political climate debate. In short, it is vital that these climate models are as good as possible and work to improve the models is an ongoing process.

Climate models

The laws of physics are the foundation of any climate model and give a mathematical description of the climate system's individual components (that is, atmosphere, oceans, biosphere, ice and snow, and the earth).

Models serve two purposes. On the one hand, researchers try to reduce the complex behavior of the climate to a set of mathematical equations in the hope of getting an insight into how climatic processes work. In this sense, working with climate models has a purely cognitive dimension - in particular in the case of the relatively simple models. On the other hand, when dealing with more complex climate models (also called general circulation models), the purpose is instead to simulate the entire climate system (that is incoming and outgoing radiation, air movement, cloud formation and precipitation, growth of ice sheets and melting etc.) even if things become so complicated that it is not always fully understood what is going on. The equations are adjusted (within reasonable limitations) so that the model reproduces as well as possible past and present climate as we know it from actual observation. Then the model can be used to predict how climate will evolve in the future.

Climate Models and the laws of physics



Exchanges of kinetic energy, heat and moisture between the columns.

Exchanges of kinetic energy, heat and moisture between the individual layers in the column.

Vertical exchange between the individual layers of kinetic energy, heat and salts by diffusion, convection and upwelling.

Horizontal exchange between the columns by diffusion and flow driven by pressure differences.

Credit: Hadley Center, UK

Schematic illustration of how a climate model is constructed. Land surface is divided into a grid with approx. 200 km between points, typically with 30-40 layers in atmospheric models and 20-30 layers in oceanic models. The figure also shows the energy flows and processes simulated in the models.

For a climate scientist, the atmosphere is essentially a system determined by the laws of physics and these laws can be expressed quantitatively by mathematical equations.

If we know today's atmospheric conditions, we can use these equations to calculate its state in the future. Because of the inherently chaotic nature of the climate system and the equations that describe it, the calculations will become increasingly inaccurate the farther we try to look into the future. While this is a significant problem for weather forecasts, the problem is less important to climate researchers who are more interested in the average weather over a longer period than in the weather on a particular day. This average, which we call the *climate*, is essentially determined by boundary conditions such as the CO_2 content in the atmosphere and solar radiation.

The most important laws of physics which are incorporated in climate models are:

- Equations of motion (Navier-Stokes equations) based on Newton's laws.
- Mass and energy conservation.
- Equations for the state of ideal gases.
- Radiation equations describing how solar and thermal radiation is propagated and converted in the atmosphere.

Aside from these laws, which are based on well established principles of physics, the models also contain empirical laws, that is relationships based mainly on observations and which do not necessarily have a solid theoretical basis. These empirical laws often describe processes that take place on time and space scales beyond the resolution of the models. The empirical laws often contain parameters that are set by "tuning" (that is they are tweaked, until the model behaves in a reasonable way). The formation of clouds being one example; the lifecycles of clouds can hardly be modeled by climate models. Clouds often form and disappear in models depending on the relative humidity.

Another example are gravity waves which occur in the atmosphere. When an air mass that is in equilibrium with its surroundings moves vertically into an area of different density, the earth's gravitational field pulls the air mass back toward the point of origin. This results in an oscillation around the point of equilibrium. These gravitational waves are essential for the development of the middle atmosphere, but have a wave length that is much smaller than the model resolution. Therefore, the formation and spreading of such waves are described by simple equations based on a combination of observations and theoretical considerations.

A fundamental problem when researchers try to assess the quality of a climate model is that they cannot, as is the case with weather forecasting models, systematically compare the predictions they produce with real life observations. Climate models are instead tested by examining how well they can describe the current climate and climate variability throughout the 20th century. Today, the best models are able to reproduce the development of global temperature over the last 100 years. In addition, they are able to simulate essential characteristics of the current climate, including the geographical variation on a large scale. The models can also reproduce the cooling effect of major volcanic eruptions.

With regard to future climate developments, climate researchers use models to assess the climatic impact of external effects. The effects can have both natural causes, such as changes in solar radiation, or they can be anthropogenic in nature, like an increase in greenhouse gas emissions or a change in the earth's surface properties due to logging, etc.

Such impact assessments are very difficult make, since climate models are not sufficiently detailed to be able to describe all elements of the real world's climate. The greatest weaknesses of today's climate models are in predicting clouds and the hydrological cycle; most models also have shortcomings in their simulations of the middle atmosphere as well.

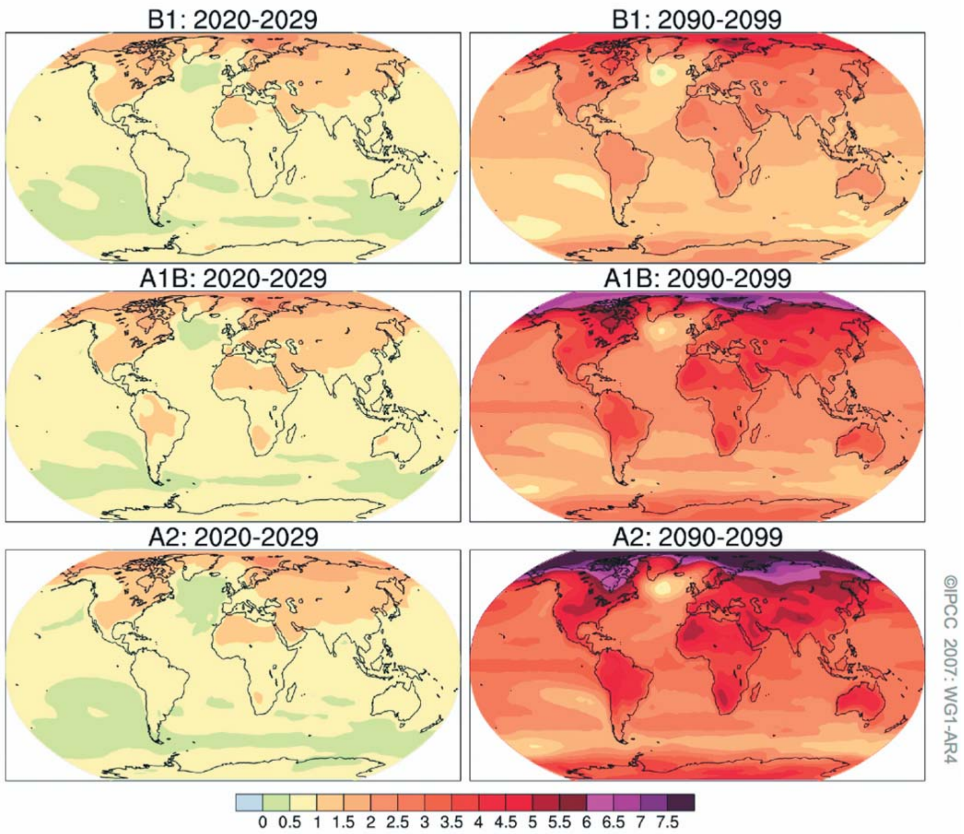
The structure of climate models

A climate model is essentially constructed like the atmospheric models used for weather forecasting. A climate model simulation starts off with a given set of initial conditions and calculations are made for small time progressions of 2 to 30 minutes, depending on the model. In a weather forecast model, weather is normally simulated up to 10 days ahead in time, while climate models run simulations for many years into the future. As climate researchers are interested in average values, climate modeling is not dependent on the initial conditions of the simulation, but only the so-called *boundary conditions* such as atmospheric CO_2 content, volcanoes and the earth's surface.

A climate model can be either purely atmospheric or a coupled atmospheric-oceanic model. Climate models, like weather forecast models, contain descriptions of conditions on the earth's surface as well as the upper layers of the soil,

Photo: Peter Bondo

How much ice is going to melt? That is one of the many questions that climate models try to answer.



Credit: IPCC

IPCC scenarios

The colored maps show the temperature development on the Earth's surface in a series of future scenarios of greenhouse gas emissions. The maps represent an average of the estimates from different atmosphere-ocean-climate models. The most optimistic scenario (the B1 scenario) is based on a future characterized by high economic growth, low population growth and rapid introduction of energy efficient technologies, resulting in low greenhouse gas emissions.

Dry river in Africa.

Photo: Colourbox

where the fundamental variables are temperature, humidity and snow cover. There are also a large number of parameters in climate models that describe surface properties, such as vegetation types and soil conditions.

As for weather forecasting models, climate model variables are organized into a grid which determines the spatial resolution by which the variables in the model can be described. For both the global atmosphere models and the ocean models, the horizontal distance between the grid points is typically a couple of hundred kilometers, while vertically there are typically 30 to 40 layers in atmosphere models and 20-30 layers in ocean models.

The significance of processes taking place at spatial scales that are smaller than the model grid must be calculated based on the fundamental variables. It is important to include these so-called parameterized processes as accurately as possible, so that their overall impact on the fundamental variables in the grid is described as well as possible. Examples of important parameterized processes in the atmosphere one should mention are radiation, cloud formation and precipitation, and processes on and in the soil. It is essential that these processes are described by physical laws whenever possible and not by empirical relationships, otherwise one cannot be certain that the description will still be valid when the climate changes. The difference between the various climate models that are used today lies primarily in the description of the parameterized processes.

What do the models predict?

The report from the International Panel on Climate Change (IPCC), published in 2007, assessed future climate development based on a number of scenarios for greenhouse gas emissions. For the next two decades, climate models show a temperature increase of 0.2°C per decade for all the IPCC scenarios, in which no political intervention against greenhouse gas emissions are accounted for.

If, however, we imagine that the concentrations of greenhouse gases and particles (aerosols) were maintained at the year 2000 level (which it already is too late for), the increase would be reduced to 0.1°C per decade.

Climate developments in the late 21st century will increasingly depend on the global emissions of greenhouse gases. The current rate of greenhouse gas emissions, not to mention emissions at a higher rate, will cause even more warming. The probable temperature rise described in the different emission scenarios lies somewhere between 1.1°C and 6.4°C by the end of the 21st century. Such an increase in temperature can lead to a number of changes in the global climate system; changes which will probably be greater than those we have experienced in the 20th century.

Even if we manage to stabilize the level of greenhouse gas emissions, anthropogenic warming and sea level rise will continue for centuries due to the time scales of the climate processes and their various feedback effects. Even with a scenario projecting low emissions, climate models indicate further warming of about 0.5°C after the year 2100 and a global sea level rise due to the thermal expansion of water of 0.3 to 0.8 meters in the year 2100 and further, though slower, increases thereafter. ■

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Further Reading:
www.dmi.dk
climateprediction.net
www.ipcc.ch
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Climate and Climate Change

English

Science is the only sensible foundation for the tough decisions facing the international community in terms of climate and climate change. However, in order to get everybody on the bandwagon it is of outmost importance that both politicians, trade and industry as well as the general public achieve a greater insight on the climate. Here we portray Danish climate research and climate knowledge through seven easily accessible articles written by the researchers themselves.

We will take you on a tour through the dwindling arctic ice, the intricate workings of CO_2 as a greenhouse gas and the causes for natural climate variability and how to distinguish it from the anthropogenic changes taking place right now.

Enjoy the journey.

Deutsch

Wissenschaft ist die einzige vernünftige Grundlage für die schwierigen Entscheidungen, welche sich der internationalen Gemeinschaft hinsichtlich der Bewertung von Klimasituationen und Klimaänderungen stellen. Wie auch immer, um jeden auf den Zug aufspringen zu lassen, ist es von entscheidender Bedeutung das Politiker, Vertreter der Industrie und des Handels sowie die allgemeine Öffentlichkeit einen größeren Einblick in die klima-relevanten Prozesse gewinnen. Hier geben wir einen Überblick über den Dänischen Beitrag zur Klimaforschung und zum Klimawissen: sieben, leicht erhältliche, wissenschaftliche Artikel.

Wir nehmen sie mit auf eine Reise durch das schwindende arktische Eis, die komplexen Wirkungsweisen von CO_2 als Treibhausgas und die Ursachen der natürlichen Klimavariabilität sowie deren Verschiedenheit von anthropogenen Änderungen.

Genießen Sie die Reise.

Español

La ciencia es la única base racional sobre la cual, la comunidad internacional puede tomar las complejas decisiones, que son necesarias en términos del clima y los cambios climáticos. Para conseguir que nos unamos todos ante este problema es importante que los políticos, las empresas y la población en general, tengan un mejor conocimiento sobre el cambio climático. Aquí presentamos un extracto de la investigación del clima y nuestros conocimientos de este en Dinamarca, a través de siete artículos de fácil acceso, escritos por los propios científicos.

Te llevaremos de viaje a través del hielo del Ártico que está desapareciendo rápidamente, por la complejidad del CO_2 como gas de efecto invernadero y hasta las causas de la variabilidad natural del clima y la manera en la cual la podemos distinguir de los cambios antropogénicos, que ocurren hoy en día.

Le deseamos un buen viaje.

Français

La science est le seul fondement raisonnable pour les décisions difficiles que doit relever la communauté internationale en termes de climat et de changements climatiques. Toutefois, afin de permettre à tout le monde de monter à bord du train, il est d'une importance capitale que les politiciens, les gens du commerce et de l'industrie, ainsi que le grand public acquièrent une meilleure compréhension sur le climat. Ici, nous présentons la recherche danoise sur le climat et sur la connaissance du climat à travers sept articles accessibles qui sont écrits par les chercheurs.

Nous vous emmènerons dans une tournée à travers la fonte de glace de l'Arctique, les rouages complexes du CO_2 comme gaz à effet de serre, les causes de la variabilité naturelle du climat et la manière de les distinguer des changements anthropiques qui se déroulent en ce moment.

Profitez du voyage.

Русский

Наука является единственной разумной основой для принятия решений, стоящих перед международным сообществом в связи с глобальными изменениями климата. Однако, для достижения большего понимания климатических изменений, особенно важно привлечь внимание всех: политиков, экономистов, представителей промышленности и широкой общественности. Мы предлагаем вашиму вниманию достижения датских исследователей климата опубликованные в статьях.

Эти исследования проведут Вас через тающие арктические льды, сложные механизмы работы CO_2 как парникового газа, откроют причины естественной изменчивости климата, происходящих в настоящие время, и научат отличать их от антропогенных изменений.

Воспользуйтесь этой возможностью.

中文

科学是国际社会面对气候和气候变化做出艰难抉择所仰仗的唯一合理基石。然而为了争取所有人的参予，重要的是使政治家，工商界以及全体民众都能对气候领域有更深入的了解。这里我们通过七篇由科研人员自己撰写的通俗文章来展示丹麦的气候研究和成果。我们引领你了解正在急剧减少的极冰，有关二氧化碳作为温室气体的复杂机制，自然气候变化的成因，以及我们如何将之与目前正在发生的人类活动导致的气候变化予以区分。