SweClim

SMHI

No. 86, 1999

Reports Meteorology and Climatology

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Cover illustration: Present-day local climates.
Photography by Stefan Gollvik

RMK
No. 86, 1999

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Report Summary / Rapportsammanfattning

Issuing Agency/Utgivare Swedish Meteorological and Hydrological Institute S-601 76 NORRKÖPING Sweden	Report number/Publikation RMK No. 86
	Report date/Utgivningsdatum September, 1999

Author (s)/Författare

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Title (and Subtitle/Titel)

On the climate change debate

Abstract/Sammandrag

The debate on the ‘science of climate change’ focuses mainly on 1) whether the climate is changing and 2) if mankind’s activities play a role in climate change. This report was written after the symposium on “Man-made versus natural climate change; Changes in climate during the past 100 years from a Holocene perspective” at the Royal Swedish Academy of Sciences, March 1999, where these issues were also dealt with. The report provides some additional background, review of some recent work on climate and includes some more philosophical reflections as well. The following topics are addressed, in some detail:

- introduction to the climate change debate
- what is known of climate (change) in the near past and in geological time scales
- how climate variability and climate change are interrelated
- what factors force climate (change and/or variability)
- some observations relevant to the climate change debate
- some recent climate modeling relevant to the climate change debate

Key words/sök-, nyckelord

Climate change, global warming, climate change debate, climate modeling, climate data

Supplementary notes/Tillägg	Number of pages/Antal sidor	Language/Språk
This work is part of the SWECLIM programme	27	English

ISSN and title/ISSN och titel

0347-2116 SMHI Reports Meteorology Climatology

Report available from/Rapporten kan köpas från:

SMHI
SE-601 76 NORRKÖPING
Sweden

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Foreword

Discussions and debate on whether or not 1) the climate of the Earth is changing at present and 2) if mankind's activities have to do with this are topical issues. The 'science of climate change' continues to provide study and evidence for them both. The present paper expands these topics reviewing both peer-reviewed papers and printed commentaries.

This report was written after attending the symposium on "Man-made versus natural climate change; Changes in climate during the past 100 years from a Holocene perspective" at the Royal Swedish Academy of Sciences, March 1999 (for a summary see *Karlén et al.*, 1999). The aim has been to cover the issue in more detail but still in a way and form that could interest a wide body of potential readers. The quoted references are by no means a complete set, but do highlight many of the relevant aspects. The present paper also includes some reflections, though a serious attempt has been made to be objective. To set the reader in the right state of mind, the definition of *debate, science* and *model*, as they appear in a normal dictionary, are provided below:

Debate = *a discussion involving opposing points*
Model = *a tentative description of system or a theory that accounts for all of its known properties*
Science = *the observation, identification, description, experimental investigation and theoretical explanation of natural phenomena; methodological activity, discipline or study*

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) process has in the 1990's become the main forum for the study of climate change. The strength of the process is that it has gathered hundreds of frontline scientists and linked them to the political forums. Within IPCC, assessments and other activities have been produced. A more definite position was adopted in the IPCC 1995 assessment (*Houghton et al.*, 1996), stating that '**The balance of evidence suggest a discernible human influence on global climate**'. Note that the statement indicates that something, in addition to natural variability, seems to be happening to the global climate, but that it does not state how much. The work done on the science of climate change thereafter has certainly not made the statement less actual. At the same time, there have been and still are cautionary voices (of some scientists and of those belonging to different interest groups) either claiming that climate is not changing due to mankind's activities or arguing that the IPCC-statement is at least premature.

That the science (of climate change) is debated is not strange. Throughout history, the driving force in sciences has been debate, debate and debate, the ability of people to innovate and to break barriers made of once 'accepted' or 'established' facts. Of course, whether the voices criticizing or the voices promoting the concept of an ongoing climate change and that there is a distinguishable man-made component in it are the innovating ones can be a matter of preference.

Using the concept of 'science of climate change' implies that the only statements that can be made necessarily carry some probabilistic component. Statements in the name of science must be based on (limited amount and accuracy of) observations, (existing forms of) analyses, theories (that have been innovated), modeling experiments (that are practically possible) and validation of theories and experiments (that is practically possible). From a philosophical point of view, it is impossible to prove a theory right. In principle a theory can only be proven to be wrong. One observation in conflict with predictions is enough to disprove a theory. On the other hand, though observations tell us about the real world, they can give only a sample of the whole truth and observations also have errors. When it comes to climate, for example, observations do not cover the whole of the system, they are made with limited accuracy and always include some error. Because of this, observations need to be interpreted with conceptual, statistical or quantitative modeling. At the same time, observations are a necessary part in assessing the performance of models. Models, on the other hand, can be evaluated and their performance can be demonstrated or disreputed for a number of cases but akin to theories, models can hardly be verified or validated in the strict definition of the terms (see e.g. *Oreskes et al.*, 1994). Observations, modeling, interpretations, analysis and theories are constantly under improvement, reflecting progress in innovation.

What do these limitations inherent to theories, observations and modeling then mean within the context of climate change debate? Well, statements made by scientists on climate change and whether there might be man-made change get formulated as 'the balance of evidence..., is unlikely to be entirely natural in origin..., most simulations show..., is expected to...' and so on. The full scientific answer can never be just a single 'yes' or a 'no' (unless the question is made to include the probabilistic component). To do so would be extending the facts and even a form of lying when the message is directed to non-scientific recipients who can not be expected to be able to add the probabilistic nature of science into the given answers.

At the same time, it is clear that when scientific results are to be integrated into practical applications; risk assessment, social planning, economic decisions, policy shaping, legislation etc., the scientific way of expressing has to be translated into the appropriate application 'dialect'. The same is true in the interaction between the scientific process and the general public. Such translation is a sort of a form of art, but nevertheless a most relevant and important activity (see e.g. *Mahlman,* 1997; *Brown,* 1999).

After this philosophical dwelling on the climate change science and debate, it is time to turn to the interesting questions of: **What is known about climate change? How does natural variability affect climate? Might mankind's activities play a role in climate variability? How well is the knowledge established at present?** Some discussion and answers are outlined below. As already pointed out, these will contain probabilities and uncertainties.

2 Something is happening in the climate. The climate during the recent decades has been different than during the last centuries or longer

There are some rather certain facts on climate and on whether climate change might exist:

- Within the era of instrumental weather and climate observations (widespread since the middle 19th century), the past 30 years have been globally warmer than the earlier part of the record. Making the comparison between the last decade and the earlier record makes this even more evident.
- The climate can be traced far back in time using a multitude of proxy data. On a time scale of several hundreds, perhaps several thousands of years, the recent times stand out as atypical, at least globally.
- In climate model results, the amount of the recent decades of global mean warming exceeds the modeled limits of natural variability. On the other hand, it can not be claimed that models are able to give an exact description of climate variations in the recent decades.
- The composition of the global atmosphere is changing rapidly and radically. Trace gases (i.e. gases that only make a very small fraction of the atmosphere) interact with longwave radiation, aka 'greenhouse gases'. They are accumulating in the atmosphere. Much of these increases attribute to mankind's activities; energy production, industrial activities, traffic, deforestation and biomass burning.
- Considering the physical laws governing the atmosphere provides a direct link between greenhouse gases and global warming. A time-dependent global mean warming is a first-order response to increasing greenhouse gas amounts in the atmosphere. A more complete picture of the net response requires considering various feedback mechanisms in the climate system as well as couplings of the atmosphere to oceans, the soils and vegetation, the ice sheets and carbon cycle. Some of these enhance the first-order warming and some slow it down.

To elaborate on these topics is not too easy. The complicated nature of the climate system, with intertwined internal and external mechanisms and processes in the atmosphere, the oceans, the biosphere, the biogeochemical cycles and the cryosphere makes the climate a challenging system to decipher. A fundamental obstacle to tackle is the large variability that characterizes climate, the relative shortness of the monitored period and the expected weakness of the global warming till the present day. Much remains to be made more certain, but considerable progress has been done. Climate modeling provides means for the attribution of climate change to mankind's activities, based on accumulated climate data. In this attribution, focus is on special 'fingerprints' that only man-made (anthropogenic) climate change could cause in the climate system (any climate change arising from natural forcing should also bear certain fingerprints). One example of a fingerprint is the vertical profile of temperature change in the atmosphere. The addition of greenhouse gases should lead to a warming of the lower atmosphere (the troposphere) and a cooling of the upper atmosphere (stratosphere and higher levels). The fingerprinting technique has been discussed and applied to model results (see e.g. *Hasselmann,* 1997; *Hegerl et al.,* 1997; *Stott and Tett,* 1998).

Fingerprints have also been identified in monitored climate data (*Santer et al.*, 1996a, *Tett et al.*, 1996, *Santer et al.*, 1996b; for some debate, see also *Michael and Knappenberger*, 1996, *Weber*, 1996 and *Santer et al.*, 1996b).

3 What about the climates in the past?

Understanding the past climates is a prerequisite for understanding the present climate and for making scenarios for the future climate. The observed/reconstructed history of climate needs to be compared to the predicted changes, before it can be stated that climate is changing. Modeling the past climates is one of the tests of models that are used to make climate change scenarios for the future. To perform such testing, data on the past are needed.

A short overview on what is known of climates in the past is now given, going back in time from the present-day to far in the past. For brevity, the discussion is limited on the variable that is discussed most often, the mean surface temperature.

3.1 The last 150 years – the era with instrumental measurements, getting warmer?

Temperature has been measured to a significant extent and acceptable precision only since the middle 19th century. The instrumental records of global temperature, as shown below (Figure 1), have been extensively publicized and used in the climate change debate.

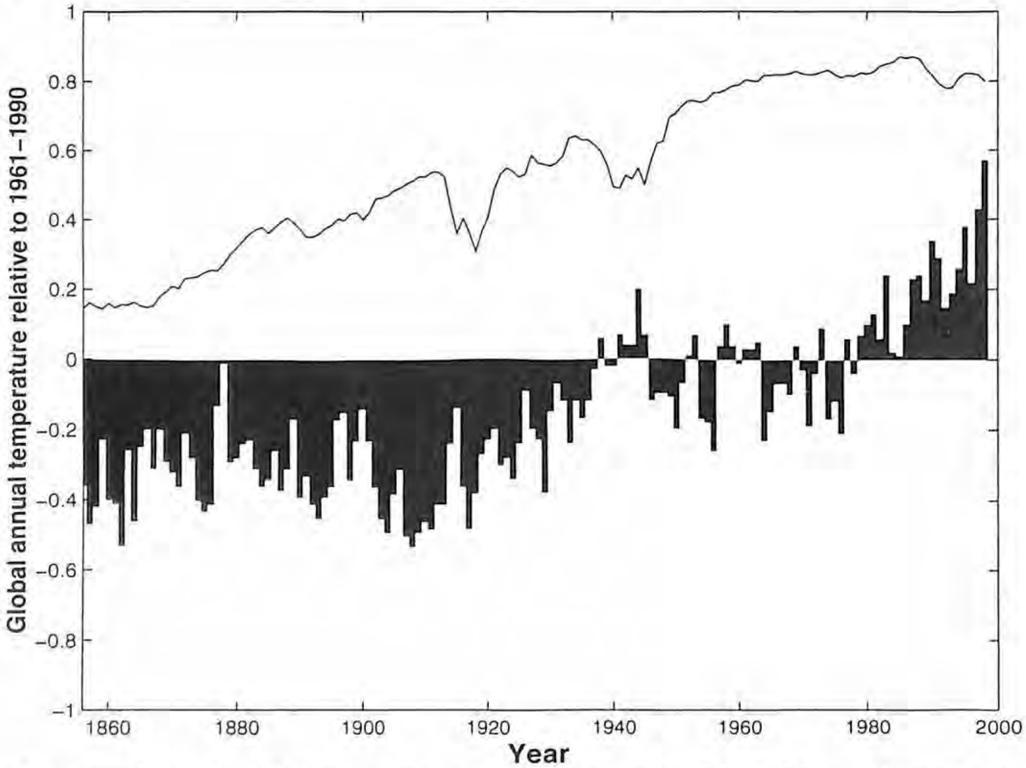

Figure 1. *A compilation of global annual mean surface temperature 1856-1998, combining (Parker et al., 1994) land air temperatures (Jones, 1994, and updates, see www.cru.uea.ac.uk/cru) and sea surface temperatures (Parker et al., 1995, and updates, see www.cru.uea.ac.uk/cru) data, shown as anomalies from the 1961-1990 mean. The reference period is a matter of choice and if a different one were used, the appearance of the graph would change. The same would happen if monthly mean data were used, or if data from only a part of the globe, e.g. one hemisphere only, were used. The line on the top half of the figure tracks the global coverage of these data (a value of one would mean a 100% coverage and a truly global mean temperature).*

The observational data suggest a global mean warming over the period. The amount of warming has been about 0.6°C (*Jones et al.*, 1999) and the warmest years since the middle 19th century are found from the last decade (during the 1990's). What is also obvious in these data is the large interannual temperature variability, even in the annual and global means.

3.2 The past climates – proxy data and their interpretation

The past climates prior to the recent era with global temperature measurement can be studied with so-called proxy data. Examples of these are man-made historical documents, corals, fossil pollen, tree rings, ice cores, ocean and lake sediments, borehole temperatures and marks left by glacier evolution. Most of these reflect local or regional past conditions so it is difficult to infer global mean climate history from them.

The borehole temperature data provide for a fairly extensive globally covering sample for the land area surface temperature history for the past five hundred years (*Pollack et al.*, 1998). The usefulness of these particular proxy data arises from the fact that surface temperature conditions propagate into the deeper soil, as a flow of heat, regulated by thermal conductivity. A constant surface temperature would give a soil temperature profile that depended linearly on depth (i.e. after reaching a depth at which the shorter-term variations such as diurnal and seasonal ones have attenuated enough). Long-term warming or cooling periods or periods with variable conditions at the surface can then be distinguished with careful analysis of the ground temperature profile. An analysis of 358 locations is presented in *Pollack et al.* (1998). They concentrated on looking for changes on a century-long time scale. Most of the sites were found to exhibit a temperature change history with warming since AD 1500. The much smaller number of sites where a predominantly very small net cooling seemed to have happened during the same long period were mentioned to have responded to regional variability (*Pollack et al.*, 1998). Reasons for such regional variability are discussed in *Pollack and Chapman* (1993). Examples are land use changes, deforestation, urbanization, groundwater flow and how well seasonal effects such as the insulating effect of snow cover, as well as regional differences in topography and geology (they affect the heat flow from the earth's interior also traversing the crust) can be treated in the analysis. One way to compensate for the regional peculiarities is to try to increase the number of the measurements and their global coverage. The deduced mean warming between the 16th and the 20th Centuries, combined from all of the 358 sites, appears to have been 1°C, on which a ±0.2°C uncertainty/variability is attributed. Furthermore, they note that half of this 500-year long change has actually taken place during the last 100 years, in good agreement with the instrumental data. An even more extensive reconstruction, combining data from 616 sites all over the global land area can be found from *www.ngdc.noaa.gov/paleo/borehole/core.html.*

As most of the proxy data are inherently local, at best regional in their information content, careful calibration between different proxies is required to derive hemispheric or global temperatures. They have to be dated accurately, possible contamination by non-climatic factors or the retrieval has to be checked for, and their relation to hemispheric or global climate has to be understood. These can be addressed in a model framework. Two recent such applications are those by *Mann et al.* (1998) and *Mann et* *al.* (1999). The former is a compilation of a number of Northern Hemisphere temperature proxy data back in time to AD 1400 (see Figure 3). The latter attempts to extend the compilation to AD 1000.

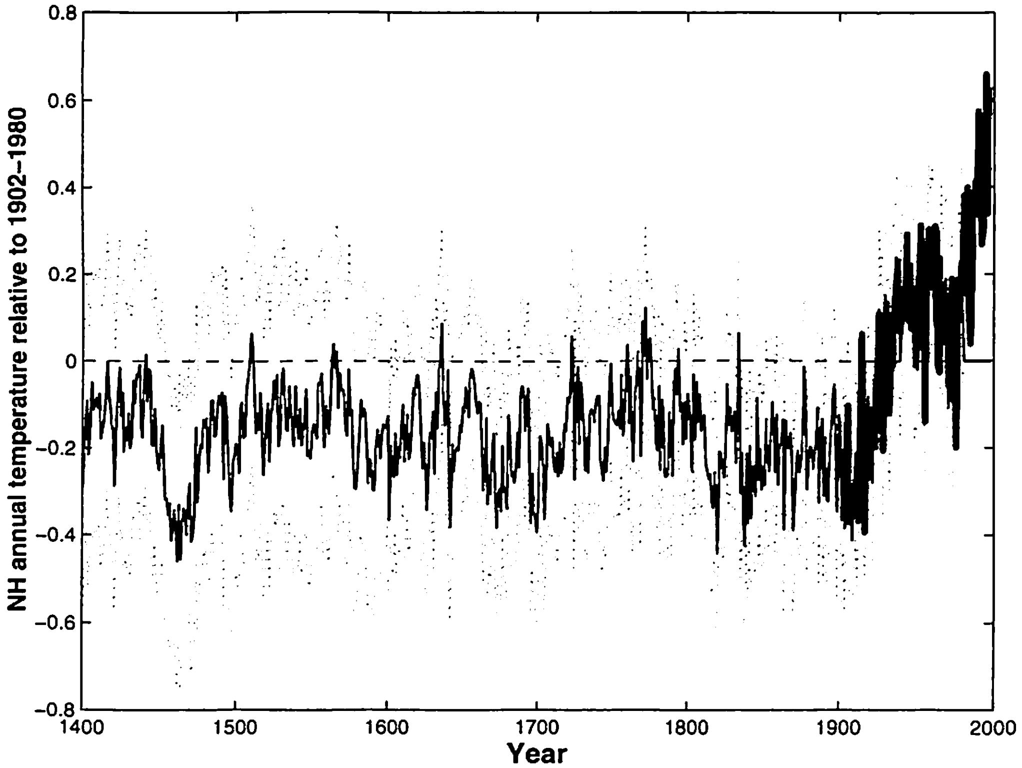

Figure 3. *Northern Hemisphere annual temperatures from AD 1400 to the present day, drawn from the data in Mann et al. (1998).*

The *Mann et al.* reconstructions are based on a multiproxy network, i.e. combinations of a number of different proxy data types and sources. The number of independent proxy sources decreases back in time. The numbers of the indicators reaching the years (AD) 1450, 1600, 1700, 1760 and 1820 are 24, 57, 74, 93 and 112, respectively. 22 of the derived climate indicators extend back to 1400. The reconstruction uncertainties increase with the decrease in the number of the derived climate indicators, i.e. also back in time. For the period between 1400 and 1000, there are even fewer data and consequently the uncertainty in the reconstruction for this period is larger than from 1400 to the present-day. The results indicate that the period between 1000-1400 would have been slightly warmer than the period 1400-1900. In addition, the 1990's has likely been the warmest decade in the last 1000 years. *Mann et al.* also located the warmest single year since 1400, possibly since 1000, from the 1990's. Since the printing of *Mann et al.,* furthermore, this record of "warmest single year" has been taken by the year 1998.

Reconstructed temperature records for yet longer time scales have been extracted from deep ice cores. The isotopic compositions of hydrogen and oxygen in the ice are a proxy data source for temperature. This time, the preserved temperature history describes the sea surface temperature at the area where the snow fallen on the ice sheet originally evaporated. Deep ice cores have been retrieved both from Antarctica and from Greenland. Climate variability on many time scales is very evident in them. The analyses also indicate that there has been some regularity in climate variability on a multitude of time scales (from periods as long as 100,000 years to about 510 years). The longest of these 'regular' periods are attributed to the orbital geometry of the Earth, i.e. changes in the eccentricity of the orbit, changes in the axial tilt and changes in the season of perihelion (the time of the minimum Earth-sun distance during the year). These three periods are about 100,000 years, 41,000 years and 22,000 years long, respectively and they are called the Milankovitch cycles. However, the orbital changes alone give quite a small forcing of climate. They require feedback from within the climate system before the changes and climate variability evident in the proxy data can be explained. Likely feedback mechanisms include changes in ice sheets of the Northern Hemisphere and responses in carbon cycling and the amount of naturally occurring greenhouse gases in the atmosphere.

Sometimes when discussing about climate change, the possibility of a new ice age comes up. The orbital forcing cycles that have affected the climate in the past are presently pushing the climate toward ice age conditions and this has actually already been happening for the past 10,000 years. With this is meant that the summertime (wintertime) insolation on the Northern Hemisphere is diminishing (increasing), along the periodicity in the season of perihelion. As the summertime change is thought to be the crucial one, a new ice age would likely ensue after some millennia, should nature be allowed to go about <u>its</u> 'business-as-usual'.

Modes of climate variability that are synchronized by the periodicities in the orbit of the Earth are quite sluggish features. Considerably shorter variability that still exhibits some regularity seems to have been occurring as well, at least during the last 250,000 years (e.g. *Dansgaard et al.*, 1993; for recent commentary, see e.g. *Cane*, 1998 and *Stocker*, 1998). Both abrupt warming and cooling events, amounting regionally up to changes of 5-7°C in as short a time as few decades (known as the Dansgaard-Oeschger cycles), have been found from ice core data from Greenland. The events are also evident from deposits in the North Atlantic deep sea bottom (e.g. *McManus et al.* 1999). These rapid regional, possible hemispheric or global, warming and cooling events, imprinted in some proxy data types, are known as 'rapid climate change events'. They were initially known to have occurred during the most recent cold (glacial) periods. Similar rapid and dramatic changes were then located even from the data extending back to the previous warm (interglacial) periods, some 120,000 years back (*Anklin et al.*, 1993). Their influence is better documented for the Northern Hemisphere than for the Southern Hemisphere. This might, however, be because of proxy data studies have been most abundant in the Northern Hemisphere. So it is not clear if the rapid climate change events were regional or even global in extent. And, if they were global, the temperature variations in the two hemispheres were not necessarily in phase. A time-lagged appearance between the hemispheres is also a possibility. Overall, the proxy data seem to carry signatures of periods of about 6100, 2200, 1450 and 510 years in length. The reasons for these or the rapid events in particular are not at all well established. Some ideas are discussed in e.g. *Broecker* (1987) and *Johnsen and White* (1989), drawing on links with the North Atlantic ocean circulation. The 6100-year period could be a result from natural ice sheet dynamics. The three shorter periods are presently ascribed to some combinations of solar variability, internal variability with interactions within the atmosphere, the oceans and ice sheets, and possibly topped by additional feedback within the climate system.

The Greenland ice cores mentioned above have been extended down to the bedrock at 3000 m below the ice surface in the so-called GRIP and GISP2 projects. The very deepest layers have to be very carefully interpreted as the weight of the glacier above has affected the structure of bottom ice and a complicated bedrock topography on which the ice sheet lies might have done the same. In any case, the longest ice cores can be used to estimate conditions back in time for 100,000s of years! Only somewhat deeper ice cores, but extending much longer back in time (the relation between the thickness of an ice sheet and the age of the bottom of it depend on the local snow fall rate) have been drilled at Antarctica. *Petit et al.* (1999) describe the Vostok ice core drilled down to 3623 m depth. The top 3310 m of this core are believed to be disturbance-free enough to permit a meaningful analysis, giving a time span of 420,000 years of past conditions. An example of the local air temperature derived for first half of this period using Vostok ice core data (drawn after *Jouzel et al.,* 1996) is shown in Figure 4. The temperature information is derived from the deuterium content measured through the ice core (the deuterium content reflects the temperature conditions at the time of the past snow that has since its fall turned into ice and got buried into the ice sheet). Periodicity in agreement with the longer orbital effects (100,000 and 41,000 years) is present in these derived data for air temperature. The shortest of the three orbital periodicities (appr. 22,000 years) is not readily obvious in the derived temperatures. Rather, this signature is seen in another variable available from the ice core, the oxygen isotope $\delta^{18}O$ that follows variations in hydrological conditions. This is explained by the sensitivity of the latter to variations in insolation that in its turn follows the season of perihelion.

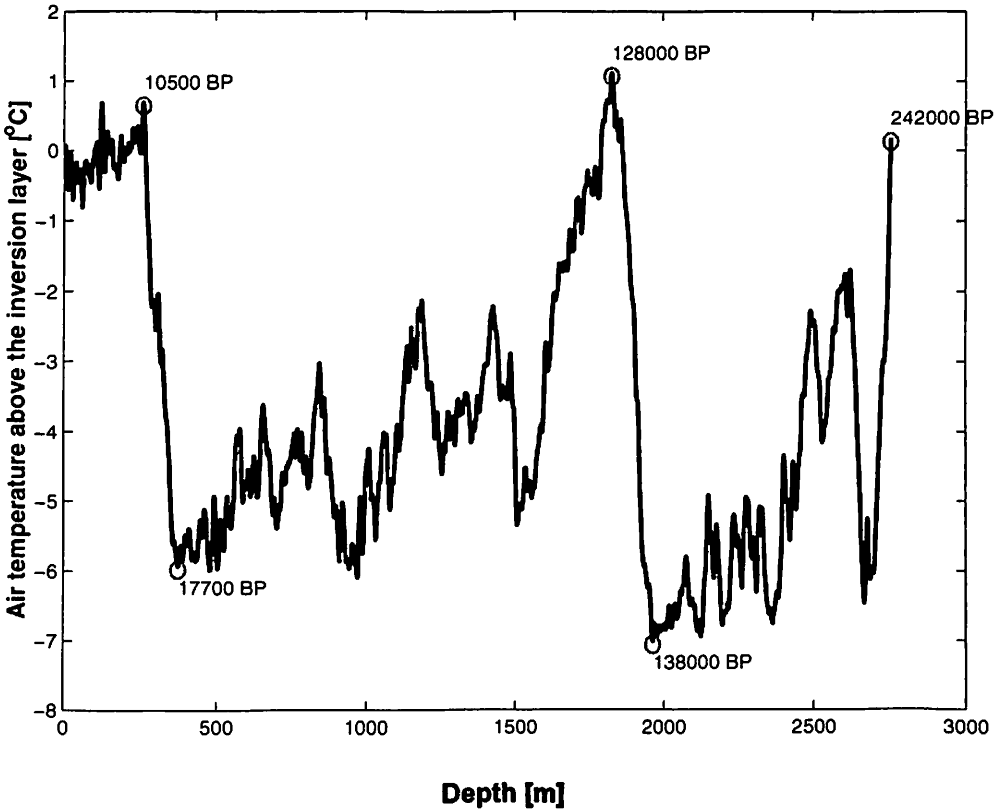

Figure 4. A 240,000 year temperature history reconstruction from ice core records drilled at Vostok, Antarctica (drawn after Jouzel et al., 1996). The horizontal axis gives the depth along the drilled ice core. Increasing depth corresponds to an earlier era. The present-day era is on the left. Some time stamps are noted in the figure (BP = years before present).

The last 420,000 years discussed above belongs to the Pleistocene, the glacial epoch that started more than a million years ago. The Pleistocene has been punctuated by short warm periods, the interglacials. The present-day belongs to the latest of these warm flips (a 'flip' in the geological sense). It is called the Holocene interglacial and it started about 15,000 years ago. The early part of the Holocene is called the Holocene climate optimum (or the Holocene Maximum) as it is believed to have been quite warm. A special feature of the present interglacial is its unprecedented length and apparent climate stability, compared to the other interglacials during the last 420,000 years. Reasons for this are not yet understood. Looking at Figure 4, one can also recognize the previous interglacial, called the Eemian, appearing about 130,000 years ago. The Eemian appears to have been even somewhat warmer in the longest Vostok record (*Petit et al.,* 1999) than the present Holocene. The two types of phases; short/warm interglacials and longer/cold glacial periods (or Ice ages) seem to have recurring during the Pleistocene, with somewhat varying transition characteristics.

The ice core results on climate variability over these long time scales illustrates even the concept of feedback in the climate system. Feedback means that the net response of climate to some forcing can be modified in a non-linear manner. For example, the changes in the earth-sun geometry due to the orbital variations are not felt to be large enough to explain the size of temperature changes between the glacials and the interglacials. Instead, it is thought that the orbital variations act as a trigger of climate change. This should lead to the response of the climate system to promote changes in the budgets and atmospheric concentrations of greenhouse gases (CO_2 and CH_4) due changes in vegetation cover and in the oceans. These add on the initial warming/cooling and lead into the second feedback step, changes in the global ice volume (deglaciation/glaciation) and changes in the surface albedo (the efficiency that solar radiation is absorbed by the surface). So far it has been difficult to conclude the order and rapidity of onset of the feedback steps, though. In *Petit et al.* (1999), it is noted that the past CO_2 and CH_4 variations do follow closely the derived Vostok temperatures (indeed, they are in phase with the temperature changes, within the timing certainty of the data). In any case, rather than being the direct cause of climate change, as at present, in the past greenhouse gas changes acted as a feedback mechanism on long orbital variations.

It has actually been possible to tread even further into the past than the last 420,000 years. The climate history has been reconstructed for millions of years into the past (see e.g. *Crowley,* 1990). To do so, not only the orbital variations, but even the movements of the continents and evolution of mountain ranges, openings and closings of channels between ocean basins, sea levels, ice sheets and atmospheric greenhouse gas levels need to be included. It is noteworthy that one has to travel back in time millions of years to find the kind of global mean warmth that climate change scenarios indicate might ensue within the next century as a result of the greenhouse gases' increases in the atmosphere. It seems that any period of the present integlacial, the Holocene, or of the previous three interglacials can at best have been about as warm, in the global annual mean, as the present-day (e.g. *Crowley,* 1990, *Petit et al.,* 1999). However, as explained in Crowley (1990), striding back to the Early Pliocene era (about 3-5 million years ago), the Early Eocene (50 million years ago) or to the Cretaceous (100 million years ago), even greater warmth than that characterizing the present climate change debate seems to have occurred. In spite of this, these periods might not be useful as analogies of the future warming as the combinations of forcing that were likely behind the past periods of global warmth and the corresponding geographical settings of the earth are very different from the present-day.

The discussion above has focused on climate variations with periodicity: the long orbit-related time scales and the much shorter rapid events. Inspections of various Holocene-records with a high time resolution reveal that nonperiodic variations that are significant enough to prompt for explanation have also been occurring. At least some of the larger of these can be attributed to volcanism. Gaseous products from major volcanic eruptions and small particles produced from these gases in the atmosphere are known to reach the stratosphere above 10 km altitude. The particles upset the radiative balance of the climate system for periods of up to some years. Impacts of solar variability, and internal variability of the climate system are likely also embedded in the nonperiodical variations. These mechanisms can have been operating individually and in combinations and adding to the periodic climate forcing factors. This of course complicates the interpretation of different proxy data and their use in improving the understanding of the sensitivity of the climate system to forcing.

4 Discussing climate change requires addressing climate variability – the signal-to-noise problem

A very basic property of climate is its natural variability on a wide range of space and time scales, including but not restricted to the regular diurnal and seasonal cycles. Climate fluctuates from year to year, decade to decade and also on much longer time scales. When climate statistics are taken over the whole globe, some cancellation occurs between anomalies of different sign, so variability is typically stronger on regional and local scales than in the global mean. Regional forcing of climate or climate redistribution (atmospheric and in the oceans) of global-scale forcing of climate can cause regional differences at any time or in the long term.

To make statements about climate and climate change, it is necessary to relate them to the variability that occurs due to natural, other than man-made, reasons. Natural variability can be further divided between natural internally and natural externally caused variability. This is in some sense arbitrary, as whether a certain forcing is external depends on the definition of the climate system. The climate system can be defined in different ways, but it is typically defined to comprise of the atmosphere (its composition, state and processes), the ocean (ditto), biomass and land cover (its state and processes), glaciers and sea ice. The interactions in this complex provide room for numerous combinations, so the climate system is inherently a chaotic one. This implies that the exact state of the system can never be fully known and certainly not predicted exactly. However, subsets (in time or space) and to some degree the overall system can be studied with great success. The statistics and the sensitivity of the system can also be tackled. This is what makes the science of climate change a reasonable and realistic endeavor. The man-made impacts on climate are said to represent externally caused variability.

The presence of variability on many scales in the climate system and how it compares to climate change is often called the 'signal-to-noise' problem in the science of climate change, with climate change as the signal and natural variability as the noise. How large natural variability can be is studied within the available observations and for longer periods by digging into preserved indicators of the climates of the past, the so-called climate proxy data. Another approach to address variability is to do climate modeling.

5 Natural forcing of climate system variability

5.1 Solar forcing

The role of solar forcing (the variability in the energy output of the sun) is an attractive topic in the climate change debate and discussion on natural climate variability. The sun is the external provider of energy for the climate system, so enough variability in the sun should bring about climate variability too. The largest obstacle to quantify this, however, is the shortness of the length of an instrumental record documenting the sun's variability. Total solar irradiance monitoring using satellites was started only about two decades ago (see e.g. *Willson,* 1997 and references therein). The monthly-to-decadal variability of total solar irradiance (its total energy output) seems to be of the order of 1-2 tenths of a per cent. This by itself should have very minor impacts on climate. Variability in parts of the solar spectrum is much larger. In the ultraviolet-part (UV) it is of the order of 100%. UV-radiation affects the stratospheric ozone layer, so a possible physical mechanism to link solar variability and climate is a secondary effect via stratospheric ozone change impacts on radiative transfer, radiative heating and circulation (see *Shindell et al.,* 1999). Some controversy exists on longer-term solar variability changes. Analysis done on the short period with satellite-monitored solar variability (*Willson,* 1996) suggests that there would presently exist an upward trend in solar total energy output of ~0.036% per decade. The analysis relies on patching together data from different instruments and is somewhat uncertain (see also *Kerr,* 1997). Anyway, if sustained on a centennial timescale, a solar brightening trend of that order might contribute significantly to global warming. Other, longer-term but indirect estimates on solar energy output trends also speak for a brightening trend, but a much smaller one: ~0.008% per decade over the past 300 years (*Lean et al.,* 1995). This longer brightening trend has been analyzed from the increase in sunspot occurrence, likely reflecting changes in solar energy output, since the distinct minimum solar activity period in 1645-1715, the Maunder minimum.

Studying solar variability back in time can only be done using historical observations of sunspots or the information stored in tree-rings and polar ice of variations of atmospheric production of cosmogenic radionuclides, ^{14}C and ^{10}Be. The latter extend back for thousands of years and they are a sort of 'double-proxy'. Their production is regulated by the penetration of cosmic rays into the atmosphere. The cosmic ray penetration in the atmosphere is affected by solar variability via changes in the sun's magnetic field. In periods of increased (decreased) solar activity, the magnetic field of the solar wind gets stronger (weaker) and it deflects better (less well) the cosmic rays from reaching the earth. Mentions of sunspot occurrence have been deduced from Chinese notes from the first century AD. Sunspots have been better followed since the invention of the telescope, i.e. from the early 17th century. The proxy data indicate rather regular solar variability at different frequencies (2300, 210, 88 and 11 years). The first documented regular type of variability in the behavior of the sun was, however, the much shorter 27-day period of rotation, found already in the 17th century as interpreted from the evolution of sunspot distribution on the face of the sun. The amplitude of the solar irradiation variations within the 27-day cycle is ~0.2%.

What is the significance of sunspots? The sunspots are darker and cooler than the surrounding region of the visible surface of the sun. The intermittent coverage of the surface of the sun by sunspots means that sun's total brightness and so its radiative output varies. A comparable modulation of the sun's brightness, but of a different sign, is due to faculae, also occurring on the surface of the sun. They are brighter than the surrounding region. When the relative occurrence of sunspots and faculae varies, so does the solar irradiance. Maybe the most discussed variability period is the roughly 11-year cycle. It was documented as late as the 1840's from observations of sunspots (the original reference is: *Schwabe, H.,* 1844. Sonnen-Beobachtungen im Jahre 1843, *Astron. Nachtrichten, 21,* 233) and often called the Schwabe cycle. The length the cycle actually varies between 9-14 years (the method of determining the length of this cycle is not well defined either). The available sunspot records also describe prolonged periods of very low or high activity. Various stars similar to our sun have been observed to have similar activity phases or levels as evidenced by the long-term proxy data for our sun. Satellite measurements indicate that the Schwabe cycle (at least during the two monitored cycles) is accompanied by solar brightness variability of 0.1-0.15% (*Lee et al.,* 1995).

Quite often, news has been made on a correlation between the solar activity and global temperature or other climate parameter variations. The length of the Schwabe cycle (though not well defined) is typically used as the measure (e.g. *Friis-Christensen and Lassen,* 1991). The correlations are typically not explained with a theory of a physical mechanism, so they maybe should not be given a high credibility rating in the 'science of climate change'. They can be seen as a relevant contribution to the debate of climate change (see e.g. *Parker,* 1999; *Kerr,* 1996, 1997), though, and not be discarded altogether either. An example of a correlation is the proposed effect on cloudiness from solar variability via the modulation of the cosmic ray flux (*Svensmark and Friis-Christensen,* 1997). The cloud effects are proposed to arise from the cosmic rays affecting the production of condensation nuclei. However, as long as the suggestion is based on a "correlation", rather than a more detailed theory, it should not be a strong component in the science of climate change.

The present-day solar effects on climate variability are likely less than the warming that has been experienced during the past 30 years. Solar effects are nevertheless believed to be a force to reckon with on discussing climate variability. Due to the smallish magnitude of this variability and as the effect can vary from a warming one to a cooling one, it is unlikely that solar variability could compensate for the projected man-made climate warming during the next century. Before the start of the alteration of the atmospheric composition by man, sun has undoubtedly played a more decisive role as a forcer of climate, possibly more than the past two decades of observations indicate. The proxy data on sun's variability and measurements made on similar stars indicate that solar variability can be larger and occur over longer periods than the available direct measurements can describe.

5.2 Volcanism

In strong volcanic events (explosive volcanism), large amounts of dust and gaseous sulfur dioxide are ejected into the atmosphere. The sulfur dioxide gets oxidized in the atmosphere, leading to a build-up of small particles that in turn interfere with solar radiation traversing the atmosphere. If left in the lower atmosphere, much of the particles thus produced are washed out from the atmosphere quite soon. The stronger the eruption and the closer it occurs to the low latitudes of the earth, the more of the gases/particles enter the stratosphere. Upon reaching the stratosphere, the particles might stay there for a longer time, of the order of 1-2 years. While in the stratosphere, they absorb and reflect incoming solar radiation, thus raising the stratospheric temperature and reducing the energy input to the lower atmosphere and the surface of the earth, with net cooling underneath as a result. A single major eruption is thought to be able to cause a global mean cooling of 0.1-0.2°C for a period of 1-2 years. The temperature response in the climate system to consequences of a volcanic event is by no means uniform over the globe. Talking about global mean effects is just a practical way for comparing the climate forcing role of volcanism to other forcing mechanisms and there might be some less evident, lingering effects as well due to the slow catch-up that oceans play with the atmosphere. A series of closely following eruptions is, however, believed to leave a deeper mark in the temperature histories, if the climate has not had time to recover in between the single events. Such a period is thought to have occurred in the first half of the 19th century, when 11 eruptions took place within 26 years. During later times, one should note that the period from 1920 to 1960 was a quiet one, in terms of volcanic eruptions. Lately, the eruptions of El Chichón in 1983 and especially of Mt. Pinatubo in 1991 were noteworthy and valuable for the science of climate change. The Pinatubo effects were reflected in the instrumental temperature records and also modeled with climate models. The consequences of the Pinatubo eruption seem to have amounted to a tropospheric cooling of a few tenths of a degree in the global mean sense, lasting for a few years.

5.3 Ocean variability

Ocean variability is certainly a player behind climate variability, and very probably an important one. Unfortunately, when it comes to understanding their role, much remains to be understood. Ocean circulation transfers large amounts of heat from the tropics to high latitudes, thus evening out differences in climate in different parts of the world. In the North Atlantic area, the so-called thermohaline circulation, a part of the heat exchange machinery between low latitudes and the arctic regions, seems to be a sensitive and important climate feature. Changes in the salinity, e.g. by freshening of the surface waters by melting of glaciers or changes in precipitation could well have been the direct cause of abrupt regional climate variability in the past. This is indicated in the climate proxy data as well as in numerical modeling. The interaction and cause-and-effect relationships between atmospheric variability and ocean variability are, however, still only poorly understood.

5.4 Land cover changes

The importance of land cover changes on climate variability has not been so extensively studied. Though such changes are inherently regional, they could add up to affect even the global mean climate. Proxy data and calculations made with simplified models seem to agree on a sizeable relationship. Deforestation, desertification, changes in lakes etc. should work on climate via albedo and hydrological feedback. In general, land cover changes can belong to both natural and man-made climate system forcing mechanisms.

6 Looking for answers on climates of the future

6.1 Climate modeling

Climate is studied with computer models. In these, the climate system is represented in terms of equations and certain conditions. These link together different parts of the climate system and specify relationships between variables that define the state of the climate system. Solving for these requires that the dimensions of the climate system, the atmosphere, the oceans, the land surface, vegetation, ice sheets etc. have to be divided into elements of some length and size. The elements the modeling thus considers are volumes of air, water and soil. For example, the continuous distributions of climate variables (air temperature, winds in a certain location etc.) have to be treated as mean values of a volume some hundreds of kilometers in the horizontal and some hundreds of meters to kilometers in the vertical. The evolution of these is then calculated in time every few minutes to hours.

The advantage of modeling is that it provides a method to gain deeper understanding of the climate system. Ideas on how the climate system works and measurements that are done get tested against the fundamental physical relationships and mathematics. It can be claimed that an essential part in seeking understanding of the climate system or any part of it involves reproducing it in modeling. Of course, ideas and measurements from the real world are used in modeling.

Climate models are also used to make scenarios of future climate. The conditions for the simulation are a description of the development of natural and/or anthropogenic forcing mechanisms. These are necessarily assumptions and as such introduce uncertainties in the modeling and consequently in the results. Another significant source of uncertainty in the model experiments is that they can only be imperfect representations of the real climate system as there are practical limitations on how models can be used as well as details of climate processes that are not fully understood. The climate system, on the other hand, is fundamentally less than fully predictable. This still leaves climate modeling as the basic available technique to look for some answers on the future climate (change). Uncertainties in model scenarios for the future can furthermore be scanned in sensitivity experiments. Examples of such are comparisons between different models (the parameterizations of the climate processes differ between models) and between different experiments with a certain model (these can test the assumptions made in the model formulation as well as the assumptions on the greenhouse gases and aerosol forcing). Experiences from model comparisons and sensitivity studies emphasize the fact that there certainly are climate processes and some components of the climate system on which much work remains to be done. One of the most well-known ones is the simulation of clouds. The need for ongoing work does not invalidate the models or their results, however.

There has been an impressive development and improvement of models since about the 1960's. At present, in the most advanced ones, the globe can be covered with a relatively high resolution (of the order of 100-300 kilometers) in the horizontal. At the same time, the models can be made to reach high in the atmosphere and deep in the oceans. These advanced models are used to make scenarios of climate change in the future, using the likely estimates on the accumulation of mankind's activities in the system (greenhouse gases, but even sulfate aerosols, the latter giving a regionally varying cooling contribution in the mean). Models that are used have also been 'validated'. This is done by simulating the climate system for hundreds, even thousands of years reproducing climate means and variability akin to the observed one and as witnessed by the climate proxy data analyses. An even more important facet is also trying to understand whether the constructed models respond realistically to a certain or changing forcing. At once, model 'validation' becomes difficult. Some opportunities are offered by simulations of past climates (cf. the discussion earlier on past climate variability) and simulations of the atmospheres of other planets of the solar system than the Earth's. In both cases, the climates to be reproduced are different from the present-day climate (on Earth) and there are (some) data to compare to. The discussion of these aspects could easily be made long. Even though it would also be an interesting one, attention is now focused on some climate model experiments that have recently been done to try to explain the instrumental temperature observations. Even though climate simulations should preferably extend over long periods of time, it is also often useful to focus only on the last 10-20 years. This is the period during which there are directly observed data on many climate forcing agents (not only on greenhouse gases, but also on particles, stratospheric ozone depletion, solar irradiance changes) and global climate observations also from satellites.

6.2 Observations during the last 20 years have indicated that during this period, the troposphere has not been getting warmer, as expected from the greenhouse gas increases alone

There seems to be a discrepancy between model simulations and temperature observations above the earth's surface during the last two decades. The latter have not indicated a warming (rather no change or a cooling) of the atmosphere off the earth's surface (*Angell,* 1988, *Christy,* 1995; *Christy et al.,* 1998), in contrast to the surface temperature data. Considering the earlier period, from ca. the late 1950's, the available observations suggest a tropospheric warming, though (see even *Oort and Liu,* 1993). Climate models forced with the observed greenhouse gas increases effects typically do produce a mean warming both at the surface and in the troposphere, even when including sulfate aerosol effects. The tropospheric measurements are from balloon-borne meteorological instruments (radiosondes) and from instruments on satellites. Modern instruments are individually quite accurate, but this has not always been the case. The coverage of the radiosounding network is spotty over the oceans and remote land areas. In addition, radiosondes as well as how they are used in different countries have changed with time, so radiosonde time series have to be carefully calibrated and analyzed (see *Gaffen,* 1994 and *Parker and Cox,* 1995). Moreover, successive satellite instruments, even of the same type, do not have the same reference/calibration level. This is a difficulty in trying to combine their recordings with the precision that would allow small temperature trends to show up on decadal time scales. Satellite-borne instruments give a global coverage, but they have been flown for a much shorter period than the radiosondes. Measurements from space are also complicated to analyze and presently only coarse resolution in the vertical can be retrieved from the longest records. *Christy* (1995) presented data from the MSU instrument, the analysis showing evidence of a cooling trend for the lower atmosphere. Later *Christy et al.* (1998) revised the analysis, still concluding with a cooling trend for the lower atmosphere, but of a smaller magnitude (cooling of ~0.046°C per decade instead of the earlier ~0.076°C per decade;

the precision of the trend is estimated at ±0.05°C per decade). Recent work on the same satellite data suggests that a slight warming trend might be evident from them instead (*Wentz and Schabel,* 1998; see also the commentaries of *Gaffen,* 1998 and *Hansen et al.*, 1998). Corrective steps reducing the cooling earlier deduced from the radiosonde data have also been discussed (*Elliott et al.*, 1994; *Parker et al.*, 1997) as well as the global representativeness of the data (*Gaffen,* 1994). Rather than proving the existence of a tropospheric warming during the past two decades, however, the latter maybe emphasizes more the fact that there are no unambiguously good quality long-term temperature records for the free troposphere. This means that it is difficult, if not still impossible to judge on long-term change or trends to exist or not. The much longer performed surface measurements, as discussed earlier, indicate a warming.

6.3 Climate model simulations en masse span some of the forcing agent uncertainties

A recent example of an effort on scanning the impact of the assumptions made in modern climate models on the model results is given by Hansen et al. (1997). They performed over a hundred 17-year climate model runs, varying the setup of the ocean component in their climate model and the inclusion, combinations and details of different natural and anthropogenic forcing agents. Only a relatively coarse model (4°x5° horizontally, nine levels in the vertical) version could be used due to the total length of the runs. Tests with a doubled horizontal resolution indicated that the quality of the model climatology was quite insensitive to this. More concern was affixed to the coarse vertical resolution and the lack of a more detailed stratosphere, making the simulation of the influences of stratospheric ozone depletion on the modeled climate more in doubt.

The different studied forcing agents were; stratospheric particles (from volcanoes), ozone change, greenhouse gas changes, solar irradiance changes and a constant forcing term to explore the sensitivity to other suggested but less well quantified forcings, such as sulfate particles in the troposphere and land use changes. Where the data were available, the forcing histories were taken from the 1979-1996 period, as observed. The study thus covers the recent period when important disagreement between climate models and measurements seems to have been the case. *Hansen et al.* (1997) also elaborate on the limitations of their approach. Their list includes vertical resolution of the model, how the interactions between the atmosphere and the surface are included, their lack of tropospheric particles and some of the forcing assumptions made, lack of high quality real world climate observations and the shortness of the considered model period.

Incorporating the full suite of forcing agents, these model simulations en masse showed agreement with climate observations in 1979-1996. Accounting just for the true greenhouse gas increases, there should have been a stronger than the observed amount of surface warming. However, the modeling indicated that the greenhouse gas radiative forcing was largely offset by the cooling contribution from stratospheric ozone depletion and volcanic aerosols in the stratosphere. That these radiative factors were indeed active (in the model but also likely in the real world) was evidenced by the changes in the modeled vertical temperature structure as they were introduced. Furthermore, it was concluded that the beginning of the period was marked by a disequilibrium in the planetary radiative balance. This represented the forcing agent histories (mainly greenhouse gas increases that had already loaded the climate system, especially the slower-responding oceans, with a warming impact). The two cooling mechanisms that came into play since 1979 were the stratospheric ozone depletion that became evident in the mid-1980's and the two large volcanic eruptions of El Chichón in 1983 and Mt. Pinatubo in 1991. The stratospheric ozone depletion phenomenon is believed to be on its way to be flushed out of the climate system, given that the international agreements on the curbing of the emissions of the ozone-depleting chemicals will hold (and no new surprises by the nature are in the pipeline for us). The occurrence of volcanic eruptions is unpredictable, so how they will act in the climate system in the future is not known.

6.4 Modeling studies on the role of natural and anthropogenic forcing on climate of the 20th century

Tett et al. (1999) examined how their climate model could represent the observed global-mean temperature increases that have been felt close to the surface since the late 19th Century. The model used was the Hadley Centre HadCM2 coupled ocean-atmosphere general circulation model (*Johns et al.,* 1997; *Tett et al.,* 1997). *Tett et al.* (1999) ran different combinations of types of forcing that might explain the experienced warming; inferred/observed solar forcing variations, volcanism, the recorded increases in greenhouse gases in the atmosphere and a corresponding development of sulfate particles in the troposphere from mankind's activities. The results were interpreted as decadal averages and they demonstrated that both the solar forcing and the anthropogenic forcing (greenhouse gases and sulfate particles) are likely factors explaining the temperature behavior during the last 100 years, though in a complementary manner. Explosive volcanism during the same period was too infrequent to show up in the decadal averages. When they considered the different forcing components in isolation and as combinations, the global temperature behavior in the early part of the century could have resulted from the combined effect of solar and anthropogenic forcing, topped by natural variability. Since the middle of the century, the anthropogenic factors were growing in importance. At first they were largely compensating as they had different impacts on the global mean temperature (greenhouse gases promoting a warming and particles a cooling). Since the 1970's, however, the anthropogenic warming impact dominated. As a summary, to obtain any kind of match for the century-long observations, they noted that anthropogenic forcing needs to be considered and that the role of solar variability was decreasing with time during the last 100 years.

6.5 Modeling the temperature of the troposphere during the last 20 years – warming, cooling or a period of no change?

Bengtsson et al. (1999) also discuss the discrepancy between model simulations and observations noted above with a series of model simulations incorporating the observed changes in greenhouse gases and some sulfate particle effects. They performed simulations with: 1) greenhouse gases (GHG), 2) GHG and a parameterization of the direct effects of anthropogenic sulfate particles (D), 3) GHG, D, a parameterization of the indirect effects of the sulfate particles and changes in tropospheric ozone (IDO), 4) GHG, D, IDO, stratospheric ozone depletion (SO) and 5) GHG, D, IDO, SO and the effect of the Mt.Pinatubo eruption in 1991. They used for this the European

Centre/Hamburg ECAHM4/OPYC coupled global climate model (*Roeckner et al.*, 1996, 1998; *Oberhuber,* 1993). The first three experiments were run from the year 1860 to year 2100. Other experiments were run for 1979-1999. The direct particle effects refer to their modification of the surface albedo; the particles reflect some of the incoming solar radiation. Their indirect effect represents the influence that small particles have to the formation and lifetime of clouds in the atmosphere, in general increasing the shadowing effect. Tropospheric ozone increases act as those of the major greenhouse gases and promote surface warming.

The increasing incorporation of the forcing mechanisms through the experiments (1)-(5) reduced the tropospheric warming simulated in the model, bringing it closer to the corresponding measurements since 1979. The stratospheric ozone depletion, the impacts of which were felt even in tropospheric temperatures, was found to have a particularly significant contribution in the reduction of tropospheric warming in the model. The inclusion of the volcanic event in 1991 had also a clear tropospheric cooling effect. After the first 1-2 years, some residual effect seemed to linger in the model, interpreted as arising from a slow response of the oceans in the coupled system. An ensemble of six simulations was also analyzed using the experiment set-ups (4) and (5). The ensemble consisted of the initial long experiment (3) and five 1979-1999 reruns with an imposed initial perturbations on the atmospheric model state. Two interesting points were raised. First, the impact on temperatures of the Mt. Pinatubo eruption was quite stable and in broad agreement with satellite observations. Second, the internal ('natural') variability on which the additional forcing superimposes modifies the simulations so that both a warming and a 'no-warming' trend appear within the ensemble members. The results and their comparison with temperature measurements off the earth's surface stress that:

- when scrutinizing only short periods (10-20 years is short for climate), whether using models or interpreting observations, natural variability is still large enough to mask the expected greenhouse warming.
- Climate models should include a fuller suite of forcing than greenhouse gases and particles only.
- How the particle (anthropogenic and from volcanoes) effects and stratospheric/tropospheric ozone changes are parameterized can be important.
- The simulated global warming, due to greenhouse gas increase, does not necessarily proceed in a steady manner. The general warming trend could well be punctuated by shorter periods with no change or even periods with some temporary cooling (the modeled temperature evolution to the 21st century results in global mean surface warming in the long simulations in the long experiments (1)-(3)).
- Both models and measurements agree quite well on long-term temperature changes in the stratosphere. The cooling at these higher altitudes is explainable by the greenhouse gas increases.

A much discussed and certainly a very relevant natural climate variability forcing mechanism is solar variability. The problem with it has been a lack of longer time series of direct measurements. Most of the past modeling studies have been able to include the solar variability in terms of the solar total irradiance only. However, it is known that the spectral distribution of solar variability is not uniform (*Lean et al.*, 1997). *Hansen et al.* (1997) made some effort to account for this by portioning the solar forcing changes into three spectral intervals. They could not provide a very thorough treatment, though, as their model was lacking a proper stratosphere. A more comprehensive treatment on this particular detail is covered by the modeling study of *Shindell et al.* (1999). They ran a series of experiments (total length of 40 years) with a global climate model with 23 layers in the vertical, extending up to 85 km altitude. Solar variability (see *Lean et al.*, 1997) was specified mimicking observations and made dependent on wavelength between 180-400 nm. At higher wavelengths, a change consistent with the total irradiance of the sun was specified. The model was complemented with an interactive chemistry scheme, thus incorporating ozone evolution due to solar variability (and feedback to radiation and dynamics), on top of the direct radiative impact of solar irradiance changes. The results emphasize that there, indeed, are important climatic effects from solar cycle variability, via radiative and induced circulation changes. The impacts on global mean radiative forcing and surface temperatures were small. Larger, regional-scale impacts were found, though.

Climate models point to a global mean warming as a consequence of increases in atmospheric greenhouse gas levels. To compile the probable range for the temperature changes in the future, assuming a particular accumulation rate of man-made greenhouse gases, results from a number of different models can be used. The range of model results then gives a range of warming 1-4.5°C to occur during the next hundred years. Assuming that the amount of sulfate particles will also increase with time, the top of this range is brought down. The "best estimate" for global mean warming till 2100, i.e. during the next hundred years is 2-2.5°C (*Houghton et al.*, 1996). To illustrate the appearance of climate warming in climate models, a compilation of the annual mean global mean temperature increase in an 80-year period given by 12 models is shown in Figure 5. These are coupled models (atmosphere, land surface, oceans and sea ice) and they participate in the CMIP2 (see *http://www-pcmdi.llnl.gov/cmip*) intercomparison project. The participating model have been run with the same, idealized greenhouse gas forcing. The 80-year simulations' length is long enough for the atmospheric concentration of the single most important greenhouse gas, the CO_2, to double. Actually, with the 1% per year increase rate that was used, the CO_2-doubling takes 70 years.

The bulk of these climate models project a global mean temperature change of 1.5-2°C as a response to greenhouse gas increases in the atmosphere. Note that these simulations extend for 80 years only. How much the extra 20 years should add to these modeled changes could perhaps be estimated by extrapolating the changes between years 60-80. This would make the century-long changes to become higher by about 0.5°C, i.e. they arrive to the 2-2.5°C warming interval mentioned earlier. The amount of internal variability evident in the bulk of these climate models amounts to ±0.2-0.3°C, i.e. much less than the projected warming trend. Something that also catches the eye in Figure 5 is that there seems to be one model that predicts a much larger warming than most. The large warming is, at least in part, caused by a strong positive feedback between increasing temperature and decreasing ice cover (*Washington and Meehl*, 1996). Also note that this model has very large (apparently excessive) internal variability, ~1°C. It is noted that results from a later version of the same model fall in line with the bulk of the models (they are actually included in the Figure).

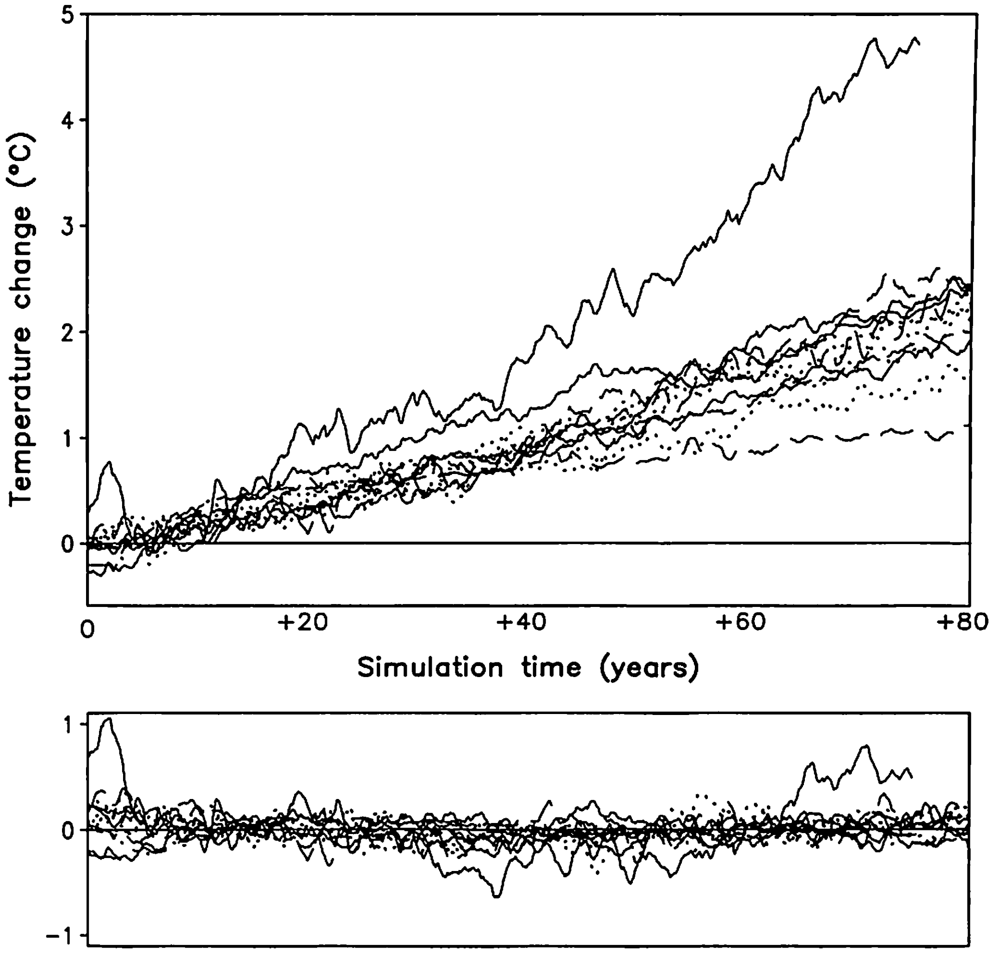

Figure 5. Global climate warming scenarios for 80 years of continuous increases of greenhouse gases in the atmosphere (top), modeled by the 12 climate models participating in the CMIP2 intercomparison. Note that the 0.6°C offset between the bottom of the panel and the zero-line approximately equals to the observed warming during the last century. The lower panel illustrates the internal variability in the models for the same simulations, shown as the detrended global mean temperature anomalies.

Could the climate model experiments described above be criticized? Certainly! Even though the amount of internal climate variability on decadal and multi-decadal scales in the models is similar to the observed, it might still be incorrectly represented. The sensitivity of the real climate system to different forcing mechanisms is not known, so are the modeled responses believable? Typically, models simulate the climate system as averages over large areas (hundreds of kilometers in the horizontal). How can they ever be able to include effects like cloud systems that are much smaller? How serious is the lack (in most models) of a proper stratosphere? Have models been empirically tuned so that they are not independent enough from the assumptions made? How realistic are the assumed forcing scenarios for greenhouse gases and particles? Are natural forcing mechanisms, such as solar variability, truthfully represented? These are all valid questions and answers on them need to be sought for. A valid question is also, however, whether the questions and uncertainties would invalidate the use of climate models or the usefulness of the results? Does the agreement, found between different models, on global warming due to continuing greenhouse gas increases and the increasingly better agreement between climate models and climate observations, for example, give enough grounds to believe in an ongoing climate change and mankind's role in it?

7 Conclusion

- The language of the science of climate change should be interpreted for the general public. The findings of the man-made influence on climate (change) and how they relate to natural climate variability are inherently probabilistic in their content.
- The science of climate uses indirect (proxy data) and direct observations and numerical models that describe the climate system. None of the data, the models or their interpretation is perfect. Being less than perfect, however, does not discredit them either.
- The surface of globe has warmed by about 0.6°C over the past 140 years and the warmest years during this time have clustered on the most recent decade.
- The 140-year global mean temperature behavior (the general trend as well as different types of variability) has been reproduced in advanced numerical models. To match the long-term measurements, man-made forcing in the form of greenhouse gases and aerosols has to be included.
- Analyses of a number of proxy data indicate that the past 30-50 years have been globally warmer than any other similar period since the 15th century.
- It is possible that the past 30-50 years have been the warmest during the past 500,000 years. This might be true even on much longer time scales.
- The possible reasons for climate variability during the last 10,000-12,000 years include solar variability, volcanism and internal variability and interactions in the climate system (atmosphere, ice sheets, oceans, land cover). On longer time scales, changes in the earth's orbit are believed to have been a trigger for the more extreme climate variability. The orbital effects would then have received feedback from within the climate system itself. These are still forms of natural climate forcing.
- The balance of evidence on ongoing man-made climate forcing, exceeding the natural one(s), suggests that there is a discernible change towards a warmer globe.
- Numerical models have been used to simulate the present climate, climates of the past and the climates of other planets. The models respond in unison to an increase of greenhouse gases in the atmosphere with a global mean warming. The details in model scenarios vary between the models, reflecting the presence of natural variability in climate, uncertainties in the model setups and uncertainties in the future climate forcing details.
- Lately, parameterizations for anthropogenic aerosol effects have been included in climate models. This has been shown to reduce the global rate of warming (as observed). The warming does not, however, get reversed or compensated.
- Increasing realism of the model results is seen when even other forcing is represented, such as solar variability, stratospheric ozone depletion and introduction of volcanic eruptions. Some impact might also arise from considering even tropospheric ozone change and resolving the spectral distribution of solar variability.
- Climate model scenarios for the outlook for climate over the next century suggest a global mean temperature increase of 2-2.5°C, or, expanding on the uncertainties, a range of 1-4.5°C. It is unlikely that any of the natural forcing mechanisms could compensate for all of it.

Acknowledgements

Erland Källén, Sten Bergström and Jouni Räisänen made useful comments during the preparation of this report. Jouni Räisänen prepared Figure 5.

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Some internet starting points to look for further information:

As expected, internet searches with the relevant keywords produce numerous links to papers, data, opinions and debate. Here are some institutional links, pointing mainly to actual data used in this review.

http://www.meto.gov.uk/sec5/sec5pg1.html (climate (change) modeling, results and impact analysis)
http://www.cru.uea.ac.uk/link (global temperature analyses)
http://www.giss.nasa.gov/ (global temperature analyses, modeling and greenhouse debate)
http://www.ncdc.noaa.gov/ (global temperature analyses)
http://www.ngdc.noaa.gov/paleo (collections of paleoclimate proxy data)
http//www-pcmdi.llnl.gov/ (climate model intercomparison pages)
http://gcrio.ciesin.org/ (Information, debate and essays, e.g. on their 'showcase links' to CONSEQUENCES, Vol 2, Number 1, 1996).

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ISSN 0347-2116