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Late Quaternary changes in climate

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Abstract

This review concerns the Quaternary climate (last two million years) with an emphasis on the last 200 000 years. The present state of art in this field is described and evaluated. The review builds on a thorough examination of classic and recent literature (up to October 1998) comprising more than 200 scientific papers. General as well as detailed patterns in climate are described and the forcing factors and feed-back effects are discussed.

Changes in climate occur on all time-scales. During more than 90% of the Quaternary period earth has experienced vast ice sheets, i.e. glaciations have been more normal for the period than the warm interglacial conditions we face today. Major changes in climate, such as the 100 000 years glacial/interglacial cycle, are forced by the Milankovitch three astronomical cycles. Because the cycles have different length climate changes on earth do not follow a simple pattern and it is not possible to find perfect analogues of a certain period in the geological record.

Recent discoveries include the observation that major changes in climate seem to occur at the same time on both hemispheres, although the astronomical theory implies a time-lag between latitudes. This probably reflects the influence of feed-back effects within the climate system. Another recent finding of importance is the rapid fluctuations that seem to be a normal process. When earth warmed after the last glaciation temperature jumps of up to 10°C occurred within less than a decade and precipitation more than doubled within the same time. The forcing factors behind these rapid fluctuations are not well understood but are believed to be a result of major re-organisations in the oceanic circulation. Realising that nature, on it's own, can cause rapid climate changes of this magnitude put some perspective on the antropogenic global warming debate, where it is believed that the release of greenhouse gases will result in a global warming of a few °C. To understand the forcing behind natural rapid climate changes appears as important as to understand the role of man in changing climate, if accurate predictions of future climate changes are to be made.

Sammanfattning

Denna litteratursammanställning behandlar det kvartära (senast 2 miljoner åren) klimatets variationer, med tonvikt på de senaste 200 000 åren. De senaste rönen inom området beskrivs och diskuteras. Sammanställningen bygger på en noggrann genomgång av klassisk såväl som ny litteratur omfattande mer än 200 vetenskapliga artiklar. Generella och specifika mönster i jordens klimat presenteras och bakomliggande orsaker till klimatvariationerna diskuteras.

Klimatet varierar naturligt och på alla tids-skalor. Under mer än 90% av kvartärtiden har stora områden på jorden varit nedisade; nedisningar har varit mer normalt än varma perioder, som den vi lever i idag. Stora förändringar i klimatet, som den 100 000 åriga nedisnings-cykeln, styrs av de tre Milankovitchska astronomiska cyklerna. På grund av att dessa cykler har olika tids-längd, så återupprepar sig klimatet aldrig exakt och det går alltså inte att hitta perfekta analoger av en specifik period i den geologiska historien.

Nya rön visar att stora klimatförändringar tycks ske samtidigt över jorden, trots att de astronomiska cyklerna förutbestämmer en breddgradsbunden tidsförskjutning. Det är troligt att samtidigheten är ett resultat av omfattande återkopplingsmekanismer inom klimatsystemet. Ett annat viktigt rön är upptäckten av snabba kraftiga klimatvariationer associerat till perioder av instabilt klimat. När jorden värmdes efter senaste istiden skedde detta i form av snabba temperaturökningar på uppemot 10°C under loppet av mindre än 10 år, samtidigt som nederbörden mer än fördubblades. Drivkraften bakom dessa snabba förändringar är inte klarlagd, men kan vara relaterad till förändringar i havscirkulationen. Förekomsten av så snabba och stora naturliga förändringar ger perspektiv på rådande växthus-debatt, där det förmodas att en, av människan styrd, ökning av CO_2 utsläpp, kan värma jorden med ett par grader. Att förstå orsakerna bakom de naturliga snabba klimatförändringarna förefaller lika viktigt som att förstå betydelsen av en antropogen påverkan på klimatet om realistiska prognoser för framtida klimatförändringar ska kunna göras.

Summary and conclusions

Knowledge about past climate on all time-scales has improved considerably during last decades. Several new concepts, now being discussed, are likely to become general knowledge in a few years and some opinions may turn out to be wrong. We try to summarise what appear to be well-founded opinions below.

- Long term variations are determined by orbital forcing, which include a 100 ka cycle caused by variations in the distance to the sun during the year, a 41 ka long cycle in the tilt of the earth and an about 23 ka long cycle in the time of the year when the earth is located relatively close to the sun.

- Each 100 ka cycle in the climate includes a long cooling period abruptly ending with a distinct temperature increase. The warm periods (interglacials) only embrace about 8% of the whole glacial cycle.

- Short-term variations are superimposed on the long-term changes in climate. A dominating, quasi periodic variation recurs with intervals of between 1000 and 2500 years. The amplitude of this variation was during Pleistocene more than 10°C, but the amplitude during the Holocene has only been 1-2°C.

- Long-term climatic variations caused by the orbital cycles are modified and emphasised by internal feed-back mechanisms. Several such are discussed, but the effect of each is so far not known.

- Among such feedback mechanisms are the atmospheric concentration of water vapour, CO_2, and other gases. The climate is also affected by forcing from atmospheric concentration of volcanic dust and variations in the cloud cover.

- Variations in the solar irradiation is another factor which appears to affect climate.

- The climate is further affected by changes in the atmospheric and oceanic circulation, which may or may not be forced by external forcing.

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Table of contents

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1 Introduction

Several processes affect climate on earth. The sun, the atmosphere, the oceans; all of them play a role in causing changes in earth's climate on various time-scales. Some of the changes and climate cycles are well documented, others are less well understood. Some theories on forcing factors are broadly accepted, others are debated.

A rationale for studying past climate is the conviction that cyclic processes drive changes in climate. With a better documentation of past climates, these cycles and the driving forces behind them will be better understood and the accuracy of climate models predicting future climates can be improved.

The Swedish Nuclear Fuel and Waste Management Co., SKB, is responsible for the management and disposal of Swedish radioactive waste. Most of the waste originates from the nuclear power plants. The spent nuclear fuel is planned to be stored in deep geological repositories. The repositories shall keep the radiotoxic material separated from man and environment for hundreds of thousands of years. During this time span long cold periods with permafrost and ice sheets over Scandinavia are expected. These climate-driven changes will affect the repository. To investigate climate-driven changes and their impact on a deep geological repository SKB has carried through a paleogeological research program (Bolton *et al.*, in progress). This report is a part of this program. Similar programs have been performed by other nuclear waste managing companies (e.g. Adcock *et al.*, 1997).

The aim of this report is to review the present state of art of late Quaternary climatic changes, through an examination of classic and recent literature, published up to October 1998. The Quaternary period comprises the last 2 million years and is divided into the Pleistocene epoch, including repeated glacials and interglacials and the Holocene epoch, i.e. the postglacial time we live in today (Fig. 1-1).

During the last decades several new archives keeping records of the past have been discovered and the geographical coverage of paleoclimatic information has increased. Improved sampling techniques permit fine interval sampling, yielding data of high time resolution. Although methods of dating also have been greatly improved, precise absolute dating is still a problem, especially when dating events older than the last glaciation. The emphasis of this report will be on the last ca 200 ka (200,000 years), for which a lot of relatively detailed information is available. The patterns of climate changes will be described, the latest findings and the most debated subjects will be high-lighted and the potential problems and doubts of the data will be evaluated.

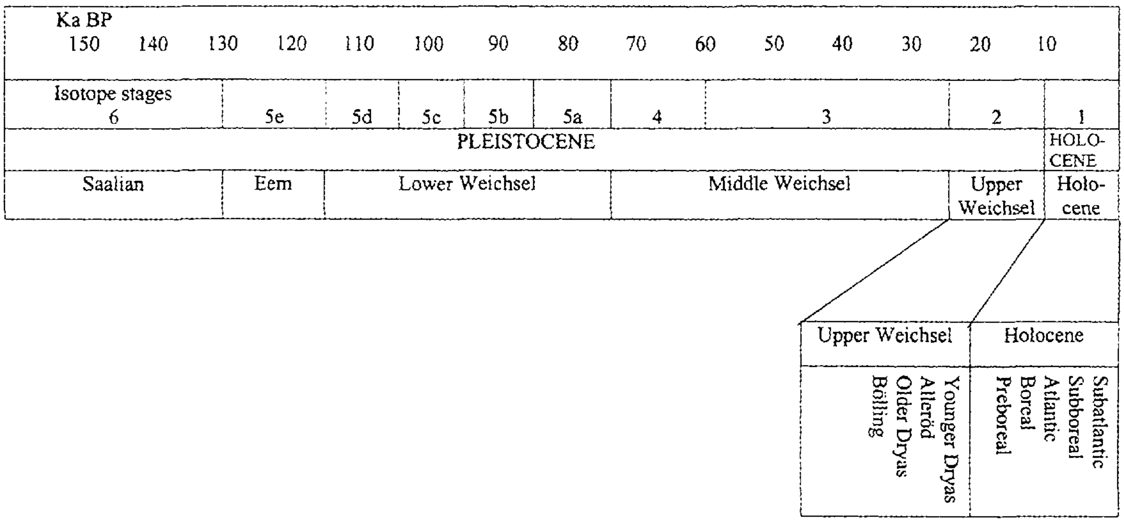

Figure 1-1. *Late Pleistocene and the Holocene stratigraphy, after Valen* et al., *1996. The upper panel indicates approximate age in ka BP. The second panel indicates the marine stratigraphy, i.e. the isotope stages. Uneven numbers denote relatively warm periods, even number relatively cold periods. The last warm period is called Holocene and the last glaciation is called Weichsel in northern Europe, Würm in southern Europe and Wisconsin in North America. A first recognised warm phase during the deglaciation was named Bölling and a second Alleröd. Two cold phases are named Older Dryas and Younger Dryas. The beginning of Bölling is dated to 14,3 ka BP, Older Dryas is a short cold event at 14 ka BP, Alleröd a warm period ending 12,4 ka BP and Younger Dryas ended and the Holocene begun 10,8 ka BP (Stuiver* et al., *1995).*

2 The Pleistocene

When James Croll, in the late 1800s, predicted long term changes in climate, the existence of one major glaciation had been suggested by Louis Agassiz and his evidence was in the process of becoming accepted. In the early 1900s A. Pencks and E. Brückner had convincing evidence for at least 4 glaciations (Günz, Mindel, Riss and Würm) on the northern foreland of the Alps, and evidence of three glaciations (Elster, Saale and Weichsel) in northern Germany (Magnusson *et al.*, 1963). First with improved deep-sea coring technique and the use of high precision mass spectrometry analyses of long cores, physical evidence of a long series of ice ages was obtained. Today, it is widely accepted that during the last 2 million years, i.e. the Quaternary period, vast glaciations on the Northern Hemisphere have occurred at intervals of around 100 ka and that the glaciation is a more normal situation for the period than the relative warm climate earth experiences at present.

2.1 General patterns

The pattern of glaciations are known for the last 1 million years from loess in China (Maher and Thompson, 1995) and at least for the last 1.2 million years from deep sea sediment cores (Raymo *et al.*, 1997) (Fig. 2-1). The $\delta^{18}O$ variations of deep-sea sediment cores[1] show that considerable amounts of water at intervals of around 100 ka have been removed from the oceans and that these long-term changes were modified by shorter superimposed variations. The pattern has been relatively regular for the last 400 ka, but beyond this time, the 100 ka cycle appears less dominant (Henderson-Sellers and Robinson, 1986; Crowley and North, 1991).

A major step was taken in the 1970s, when a chronology based on radiometric dates and magnetic reversals was constructed (Hays *et al.*, 1976). The chronology for the last 450 ka

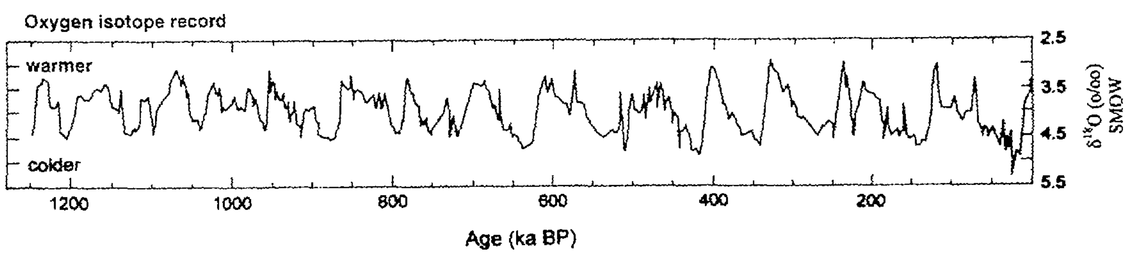

Figure 2-1. *A deep-sea oxygen isotope record for the last 1.2 million years shows the cyclic pattern of glaciations and interglacials. From Raymo* et al., *1997.*

[1]The composition of the stable oxygen isotopes ^{16}O and ^{18}O in the oceans varies as a function of how much water is bound in ice, hence variations in the $^{16}O/^{18}O$ ratio in the deep-sea sediments document shifts between glacial and interglacial times. Isotope ratios are expressed in the δ notation relative to a standard (SMOW), in parts per mil (‰):

$$\delta^{18}O = \left(\frac{R_{sample}}{R_{ref}} - 1\right) * 1000 \text{, where } R = {}^{18}O/{}^{16}O.$$

was compared with the Milankovitch cycles (this report, 2.4.1) and a slightly "tuned up" chronology was proposed, which fits this astronomical theory (Imbrie *et al.*, 1984). The justified chronology was largely accepted but has been challenged lately (Winograd *et al.*, 1992; Imbrie *et al.*, 1993; Muller and MacDonald, 1997).

A few other long records of changes in environment and climate are available. One of the real long records comes from lake sediments in Lake Baikal and yields environmental information based on changes in the composition of diatoms and biogenic silica for approximately the last 2.6 million years (Williams *et al.*, 1997). The record is well correlated with the marine record. A pollen study from north-western Greece has revealed major changes in the occurrence of trees during the last 430 ka (Tzedakis, 1993). Ice cores from Antarctica and Greenland have provided details about variations in climate during the last 100 to 200 ka (Jouzel *et al.*, 1993; Johnsen *et al.*, 1995). In addition, information about the long term climate has been obtained from other lake sediment (van der Hammen *et al.*, 1971) and cave deposits, such as stalagmites and flow stones (Bar-Matthews *et al.*, 1998a; 1998b). All these long records repeat the general pattern of glaciations and interglacials observed in the marine record and also demonstrate the occurrence of great fluctuations within the glaciations. However, the records have so far provided few quantitative estimates on absolute temperature and precipitation changes. Absolute temperature figures of any reliability are only available for the last glaciation (120–11.5 ka BP) and the Holocene.

2.1.1 Temperature

During the last two million years, climate has mainly been cold enough to support major ice sheets; only during about 8% of the time climate has been as warm, or warmer, than at present. The magnitude of the changes between glacial and interglacial climate appears to have been similar during at least the last 700 ka.

Relatively detailed information on temperature has been obtained from analyses of $\delta^{18}O$ variations in ice-cores retrieved from the ice sheets on Greenland and Antarctica for the last 200 ka. While changes in $\delta^{18}O$ in ice-cores are considered as good evidence for changes in temperature, the transformation of $\delta^{18}O$ to absolute temperatures depends on empirical observations under present day conditions (Dansgaard, 1981; Johnsen *et al.*, 1989), which is not a perfect analogue to conditions during the glaciation (Charles *et al.*, 1994). Therefore, much results have been published as a deviation in $\delta^{18}O$, indicating warmer or colder climate, rather than absolute temperature changes. However, temperature changes during the last 110 ka at the GRIP[2] ice coring site, near the highest point of the Greenland ice sheet, have been calculated based on bore-hole temperature and $\delta^{18}O$ variations. During short intervals within the last glacial, at around 70 ka and at 22 ka BP, the temperature dropped to about 25°C below the present temperature. During less cold periods temperature rose to about 5°C below the present (Johnsen *et al.*, 1995) (Fig. 2-2). Similar studies at Vostok, Antarctica, indicate a lesser decrease in temperature during the last glaciation. Lorius *et al.* (1988) were of the opinion that the minimum temperature during the last glacial maximum was 9°C lower than at present, but later the temperature decrease was calculated to have been only about 5°C below the present (Jouzel *et al.*, 1993) (Fig. 2-3). The temperature difference between Antarctica and Greenland may to some extent be a result of the resolution; the accumulation on Greenland is larger than at Vostok and therefore permits higher time resolution and also the smoothing algorithm used on the Vostok record may reduce the extreme low temperatures. The Greenland

[2]GRIP stands for the Greenland Ice-core Project.

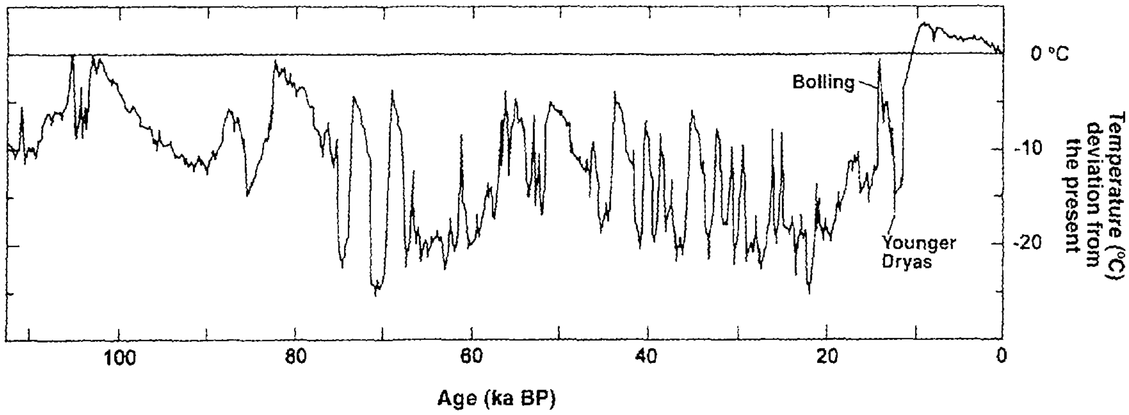

Figure 2-2. Changes in the Greenland temperature from the beginning of the last glaciation to the present, obtained from an ice-core. Note the rapid fluctuations between 80 and 10 ka BP with an amplitude of about 15°C and lasting in average about 1500 years (Dansgaard-Oeschger events). The last 10 ka, the Holocene, has had an unusually stable climate. From Johnsen et al., *1995.*

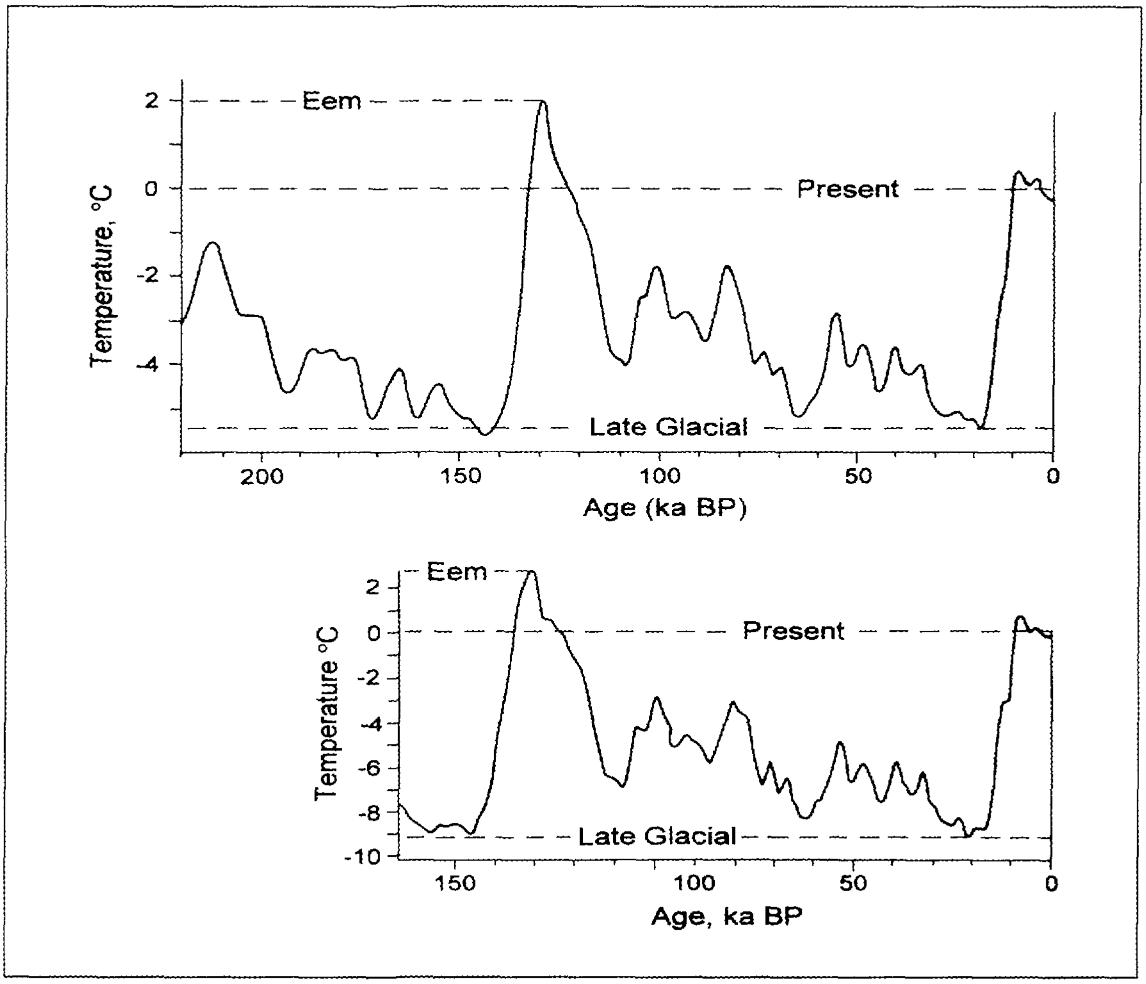

Figure 2-3. Changes in the Antarctic temperature. The lower panel shows a calculation from 1988, when the difference between the present and the late glacial maximum was estimated to 9°C. The upper panel shows a calculation from 1993, which shows a difference of slightly over 5°C. From Lorius et al., *1988 and Jouzel* et al., *1993.*

record reflects the regional response to North Atlantic temperature variations. Temperature estimates from East Antarctica for the previous interglacial, Eem, indicate warmer conditions than the present, with temperatures about 2°C above the Holocene maximum (Jouzel *et al.*, 1993). The Greenland ice core record demonstrates that a large temperature variation also took place during the Eem and that rapid temperature drops of about 15°C occurred on several occasions during this, on average, warmer period (GRIP Members, 1993).

Pollen stratigraphy and rock magnetic susceptibility studies from northern France, imply that major changes in vegetation and hence in temperature and moisture occurred also in Europe during Pleistocene (Woillard and Mook, 1982; Guiot *et al.*, 1989; Thouveny *et al.*, 1994). Using recent vegetation and modern climatic parameters as an analogue to past conditions Guiot *et al.* (1989) have estimated temperatures to be more than 10°C lower than present at several occasions during the last glaciation (Fig. 2-4). The warmest interval during the previous interglacial, Eem, is estimated to have been 1 to 2°C warmer than today. Studies of cave speleothem (stalagmites etc.) growth also indicate general warmer but a highly variable Eemian interglacial (Lauritzen, 1995; Roberts *et al.*, 1998).

Until recently, it has been believed that temperature changes were small in the tropical and subtropical regions. Based on microfossil studies of deep-sea cores, low latitude ocean temperatures were estimated to be less than 2°C colder and the world ocean temperature was in average around 2.3°C lower than present during the last glacial maximum, at 18 ka BP (CLIMAP[3] Project Members, 1976). New evidence indicates that, even in the tropics, temperatures decreased distinctly during the last glacial maximum. Sea surface temperature drops of around 5°C have been obtained from corals at Barbados (Guilderson *et al.*, 1994) and from the Indian Ocean (Colonna *et al.*, 1996). A study covering the Pacific between 25°N and 25°S shows that typical decrease in sea surface temperature was between -3 and –5°C (Bush and Philander, 1998). Records from mountain areas show a general snow-line decrease of about 1000 m at a number of sites from northern North America to Antarctica, which would indicate a global land temperature decrease of about 6°C (Broecker and Denton, 1990). Recent studies on noble gas content of ground water in Brazil and Namibia (Stute *et al.*, 1995; Stute and Talma, 1997), ice cores from Peru (Thompson *et al.*, 1995), pollen and lake levels in central and southern South America (Markgraf, 1989; Colinvaux *et al.*, 1996) also indicate a temperature decrease of around 5–6°C at the last glacial maximum. Amino acid racemisation rate-changes[4] indicate that millennial-scale average air temperatures in Australia were 9°C lower than the present between 45 and 16 ka BP, and near Lake Victoria, East Africa, a temperature decrease of about 10°C during the last glacial maximum was determined (Miller *et al.*, 1997). Temperature change of this magnitude shows that substantial cooling took place even in tropical and subtropical continental areas. The magnitude of the cooling in the tropics is the same for the latest calculation of Antarctic temperature decrease but smaller than for Greenland.

2.1.2 Precipitation

Changes in precipitation during Pleistocene and older times are not well known. Because lower temperatures lead to less water vapour in the atmosphere, precipitation is likely to

[3]CLIMAP stands for Climate, Long-range Investigation, Mapping and Prediction.

[4]Protein in skeletal remains undergoes several chemical reactions. One of these is the amino acid racemisation. The reaction is both time- and temperature dependent and can therefore be utilised both for geochronology and for reconstructing paleotemperatures (Miller, 1981).

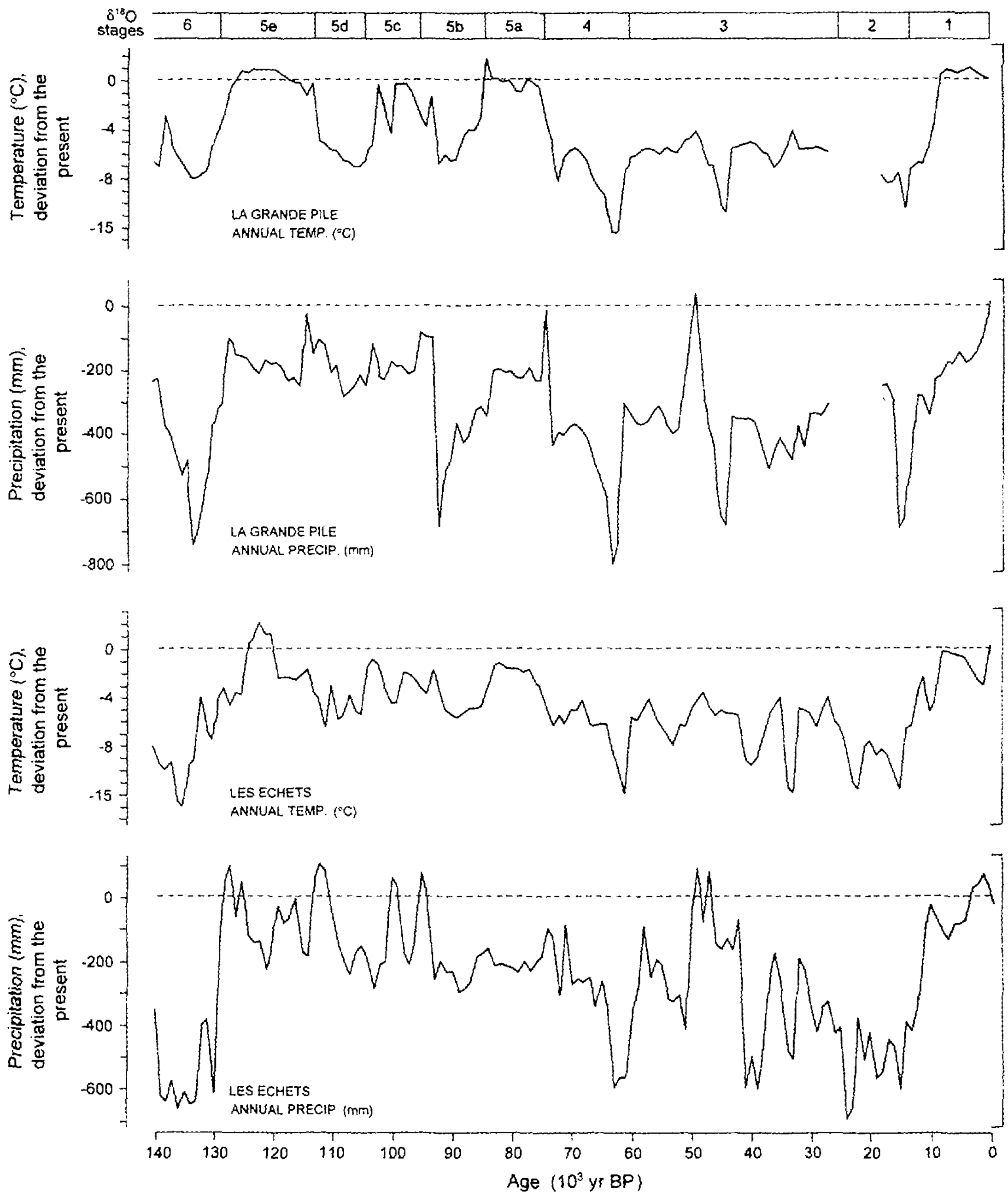

Figure 2-4. Temperature and precipitation changes at La Grand Pile and Les Echets, France. In general terms, the precipitation was lower during periods of cold climate than during warmer intervals. Temperature and precipitation is given in relation to present conditions. From Guiot et al., *1989.*

have been smaller than at present over most of the world during glacial times. Broecker (1997a) is of the opinion that variations in the $\delta^{18}O$, of 8‰, in ice cores from the Andes indicate reduced water vapour content of the Late Pleistocene atmosphere to 80±7% of today's value.

The magnetic susceptibility in paleosols can be used as a proxy indicator of past climate changes. In China, precipitation-driven pedogenesis is largely responsible for the production of fine-grained magnetic minerals that strongly influence the strength of the magnetic-susceptibility signal in the loess sequence. The pattern of the preserved paleosusceptibility in Chinese loess closely resembles the marine isotope record and is believed to reveal major changes in the paleoprecipitation during the last million years. The time-scale has been constructed by tuning the susceptibility record to the time-scale of the marine oxygen isotope record, which in turn is tuned to fit the Milankovitch cycles. The susceptibility record indicates a 25–80% increase in precipitation in the presently semiarid region and a 5–25% increase in the humid region during the last interglacial (Eem) and in early Holocene. During glacial times precipitation decreased with about 50% compare to today. Overall, precipitation was lower than present for 80% of the time back to 1.1 Ma ago. Like the marine isotope record, the amplitude of variations was lower prior to 700 ka BP than after (Maher and Thompson, 1995).

Based on a study of the ^{10}Be concentration in the Dome C ice core, Antarctica, Raisbeck *et al.* (1987) conclude that the rate of accumulation in Antarctica was about half of the present during much of the last glaciation. However, the increased concentration in ^{10}Be can, instead of indicating changes in precipitation, be a result of increased solar radiation (Beer *et al.*, 1992). Studies of annual layer thickness variations in the GISP2[5] ice-core from central Greenland, have shown that precipitation was about half of the present during the colder Younger Dryas (11,5-12,8 cal yr BP) and Older Dryas (14,5-17,5 cal yr BP) (Alley *et al.*, 1993) and also four to five times less than today during the coldest intervals within the last glaciation (Alley and Bender, 1998). The precipitation was, however, large enough to permit a major expansion of the Scandinavian ice sheet during the last glaciation (Holmlund and Fastook, 1995; Kleman *et al.*, 1997).

The European pollen records indicate great variability in precipitation with mostly lower values than the present for the last 140 ka (Fig. 2-4). In southern Africa evidence of drier conditions at 95-115, 41-46, 20-26 and 9-16 ka BP is apparent from studies of dune formation (Stokes *et al.*, 1997). Summaries of obtained information show that lacustrine sediments were deposited in several lakes in tropical and sub-tropical Africa before about 25 ka BP. Between around 10-25 ka BP (^{14}C years), a very dry climate, with low lake levels, reduced rivers and a shift from forest to grass vegetation seems to have dominated much of Africa (Butzer *et al.*, 1972; Gasse, 1977; Adamson *et al.*, 1980; Nicholson, 1980; Hamilton, 1982; Aucour *et al.*, 1994; Gasse *et al.*, 1995). Reduced precipitation in tropical East Africa led to that Lake Victoria was completely dry for some unknown period before 12,400 ^{14}C years BP (Johnson *et al.*, 1996).

The evidence of low precipitation in the tropics is supported by methane measurements in ice cores. Most methane is produced in tropical swamps and the atmospheric concentration of this gas therefore yields an indirect, but continuous record of water availability in the tropics (Blunier *et al.*, 1995). Methane concentration was relatively low, indicating dry conditions, at 40–35 ka BP, but rose distinctly around 35 ka BP. From 35 ka BP to about 24 ka BP the methane concentration decreased and remained low to about 16.5 ka

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[5]GISP stands for the Greenland Ice Sheet Project.

BP, again indicating dry conditions. Methane concentrations then increased rapidly and remained high until 13 ka BP, when it decreased dramatically for about 1000 years. These evidence of tropical wetter conditions following the last glacial maximum is only documented in southern semi-arid Africa (Shaw and Thomas, 1996). The last period of low methane, at around 12 ka BP, and hence dry conditions in the tropics, coincide with the cold Younger Dryas period but the dry conditions in the tropics lasted a shorter period.

The climate in Asia is largely determined by the summer- and winter monsoons. This circulation system is central, not only for south-western Asia, but also for a much wider area, including northern Africa. A record from a closed lake basin, Qinghai, in north-western Tibet includes sediments from the last 13 ka BP. Late Pleistocene was fairly wet in this area and abruptly became dry at the beginning of Holocene (Kelts *et al.*, 1989). A later study of lake sediments from Sumix Co in western Tibet shows that late Pleistocene was cold and dry, but wet episodes occurred (12.5 ka BP and 10 ka BP, ^{14}C years) in phase with steps of the deglaciation (Gasse *et al.*, 1991).

An ice-core from Guliya ice cap provides a record going back to 500 ka BP (Thompson *et al.*, 1997), but the resolution of the pre-Holocene ice core is poor. The $\delta^{18}O$ record indicates temperature variations of the same magnitude as polar ice-cores.

While the lower lake levels in the tropics, the lower magnetic susceptibility in the Chinese loess and the low ice accumulation rates in the polar regions are good evidence for reduced precipitation during the last glaciation, lakes in dry south-western USA seem to have been much larger at the same time. Studies of Lake Lahontan, indicate water levels higher than during much of Holocene for the period between 20 ka and 10 ka BP (Smith and Street-Perrot, 1983) and Owens Lake had higher lake levels most of the time between 52,5 ka and 12,5 ka BP (Benson *et al.*, 1996). Wet-dry conditions in the Searles Lake appear to correlate with abrupt changes recorded in Greenland ice cores (Lin *et al.*, 1998). To what extent this relatively moist conditions in western USA were a result of reduced temperature and hence less evaporation, or increased precipitation is unknown, but Lin *et al.* (1998) believe that an increase in precipitation could be caused by a southward displaced jet stream, due to the presence of a large Laurentide ice sheet.

Even South American lakes are reported to have had relatively high stands during much of the Late Pleistocene, but low lake levels are also reported for lakes located in Central America as well as Central and Southern America (Markgraf, 1989).

2.1.3 Sea level

The formation of large ice-sheets in continental areas resulted in considerable lowering of sea level during glaciations. The maximum reduction of sea level during the last glaciation remained an open question up to recently. Evidence of major changes in sea-level are found in areas with a long-term constant tectonic uplift such as Barbados and New Guinea, where corals once living at sea-level now are found much above the present sea level. If it can be shown that the high and low sea-levels were not entirely due to tectonic movements but also to glacial eustatic changes, the uranium-series dating records of the reefs can be used for identifying the time-scale for interglacial stages (Gallup *et al.*, 1994). The coral record confirms previous evidence of major changes in sea level as observed from variations in the $\delta^{18}O$ content of deep-sea cores (Fig. 2-5).

Minimum sea-levels are observed for the last glacial maximum. A study of the $\delta^{18}O$ of planctonic foraminifera from the Sulu Sea during the last 150 ka indicate a sea level of

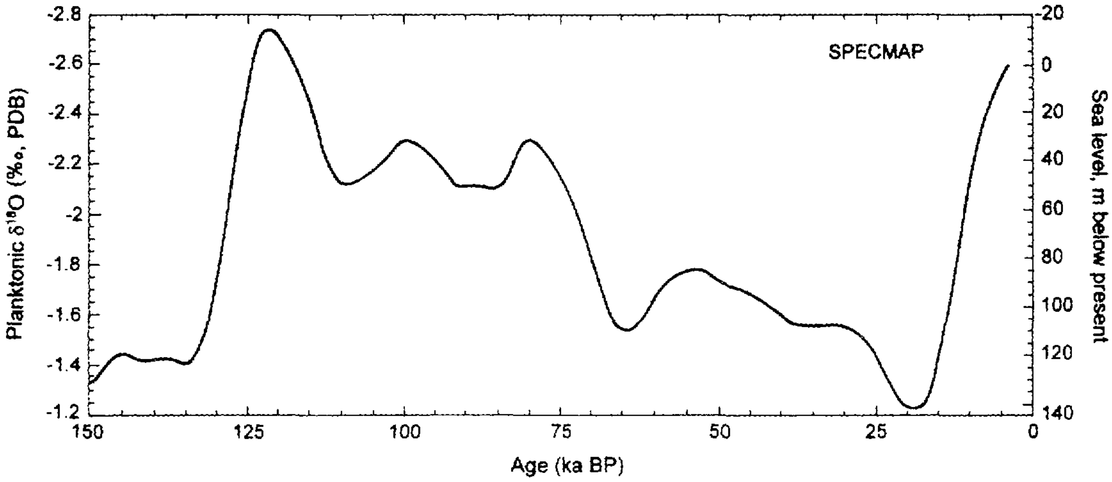

Figure 2-5. Changes in sea-level during the last 150 ka according to SPECMAP. A maximal sea-level of close to 20 m above the present was reached between 125 and 120 ka BP and a minimal level of –140 m below the present was reached about 18 ka BP. After Imbrie et al., *1984.*

about -130 m at 18 ka BP (Linsley, 1996). A slightly larger reduction, indicating a sea level as low as -145 m ±5 m at 18.4 ka BP has been obtained from coral reefs at Mayotte Reef, Indian Ocean (Colonna *et al.*, 1996).

2.1.4 Extent of glaciations

The area covered by major ice sheets in Western Europe and North America is well known, except for the Canadian Arctic. Also, the size of several relatively small ice-caps, like the one in South America and New Zealand are well known, as well as the minor ice caps formed on high mountains in the tropics, e.g. on Ruwenzori, Mount Kenya, Mount Kilimanjaro, in New Guinea and Hawaii (Hope *et al.*, 1976; Denton and Hughes, 1981; Porter *et al.*, 1977; Porter, 1981; Rosqvist, 1990).

Two models of the extent of the Scandinavian ice-sheet at the last glacial cycle have been proposed recently (Fig. 2-6). The major discrepancy between the models occur for the older Weichsel I ice, where Kleman *et al.* (1997) infer a vast ice-sheet covering the whole of Norway, north-western Sweden and northern Finland at 110 ka BP, while Holmlund and Fastok (1995) predict only local mountain ice caps to have formed. The fact that Norwegian speleothems were formed at about 110 ka BP (Lauritzen, 1995), suggests that an ice-sheet could not have extended over western Norway at that time.

Major ice sheets forming along the north coast of Siberia has been suggested (Grosswald, 1980; 1998; Grosswald *et al.*, 1992), but the size of these ice sheets are debated and questioned (Arkhipov, 1998; Michel, 1998). However, the lowering of the ocean surfaces requires more extensive ice sheets than the "classical". This is particularly true if Colhoun *et al.* (1992) are correct about that the expansion of the Antarctic Ice Sheet was minor and could only have reduced sea level by 0.5–2.5 m. The apparently too small amount of water tied up in the well known ice-sheets could be a result of incorrect estimate of ice sheet thickness. However, it is not unlikely that some of the by Grosswald proposed Siberian ice sheets existed.

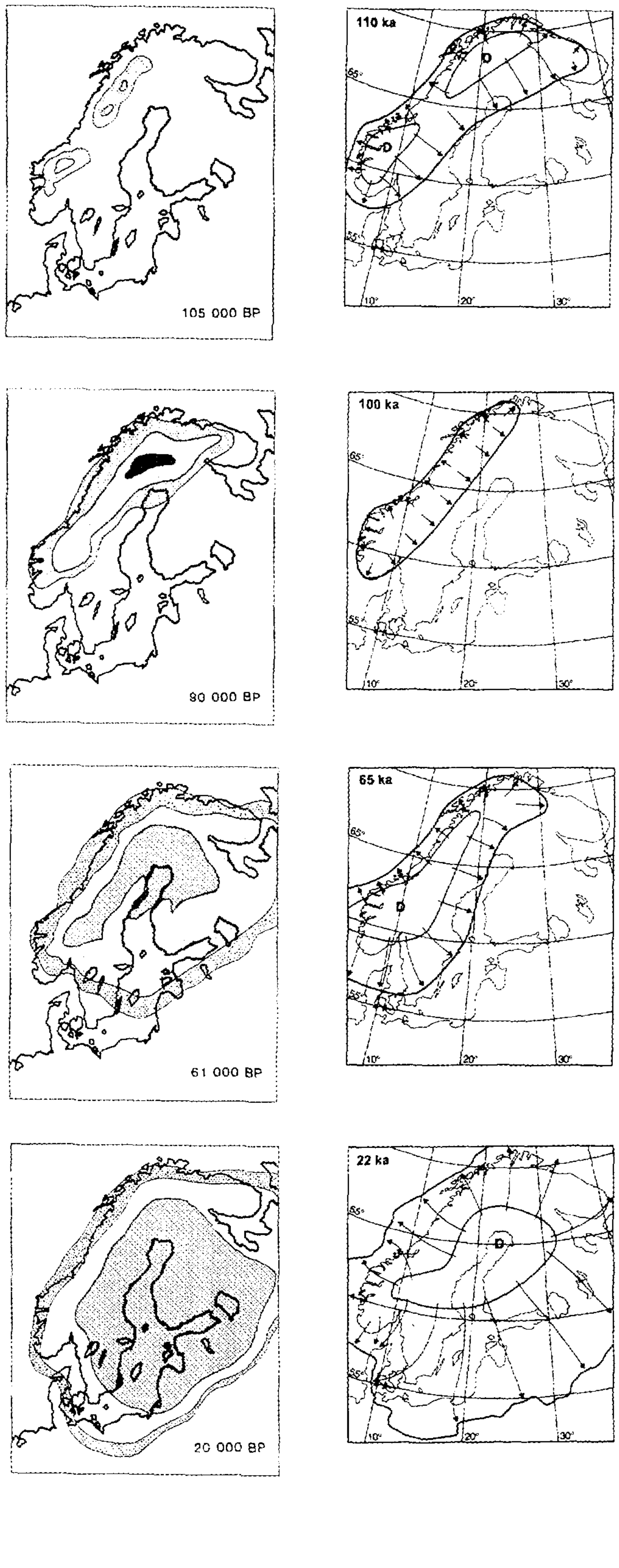

Figure 2-6. Left: Glacier expansion during the last glaciation according to Holmlund and Fastook (1995). The shaded areas denote regions covered by ice with a thickness of a) less than 1000 m (lightest shading), b) 1000–2000 m and c) more than 2000 m. Right: Glacier expansion according to Kleman et al. *(1997). D = Ice divide. The modelled ice-sheet expansion is similar although the expansion was initiated at slightly different occasions.*

The extent of glacier expansions in Tibet has also been discussed. Recent studies have revealed that large glaciers occupied valleys and formed outlet glaciers, which reached low elevations (Kuhle, 1998; Benxing and Rutter, 1998), but there are no physical evidence for that a major ice sheet covered the Tibet plateau.

2.2 Rapid fluctuations within the last ice-age

A major pattern in the Quaternary climate is the slow cooling towards the glacial maximums and the rapid warming ending the glaciations (terminations). Deep-sea sediments and Chinese loess reveal at least seven abrupt terminations (Muhs *et al.*, 1989). Less distinct terminations are also recognised beyond 800 ka BP and the pattern is still visible back to at least 1200 ka BP (Maher and Thompson, 1995; Raymo *et al.*, 1997). The abruptness of the two latest terminations is very distinct in the Antarctic and Greenland records (Barnola *et al.*, 1987; Johnsen *et al.*, 1992) (Fig. 2-7). The warming from minimal to maximal temperature occurs within a few thousand years, while the cooling takes almost 100 ka. At the same time as the temperature rises dramatically, the concentration of atmospheric CO_2 and CH_4 also increases.

The last termination has been discussed frequently. The warming seems to have taken place through a series of abrupt steps and major changes in accumulation (which largely

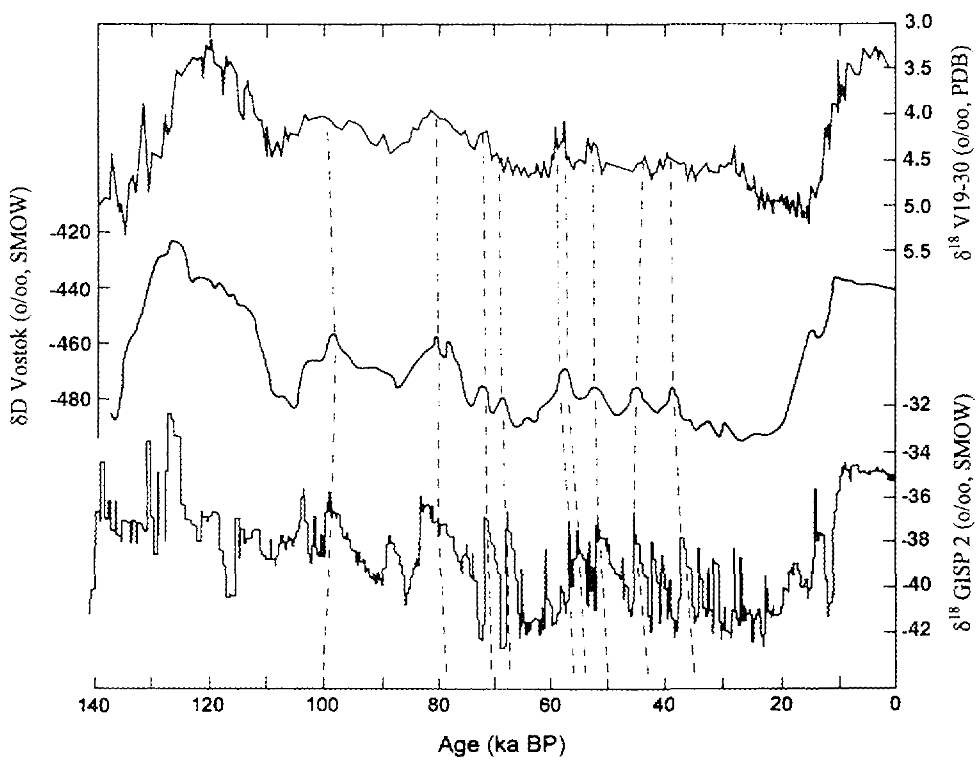

***Figure** 2-7. Major changes in the global climate occur at approximately the same time. The figure illustrates changes in temperature recorded in the Vostok ice core, Antarctica and in the GISP2 core at central Greenland. The upper curve shows variations in the bentic $\delta^{18}O_{foram}$ record from deep-sea sediment core V19-30 (3°21'S 83°21'W, 3091 m) which shows continental ice volume variations. From Jouzel, 1994.*

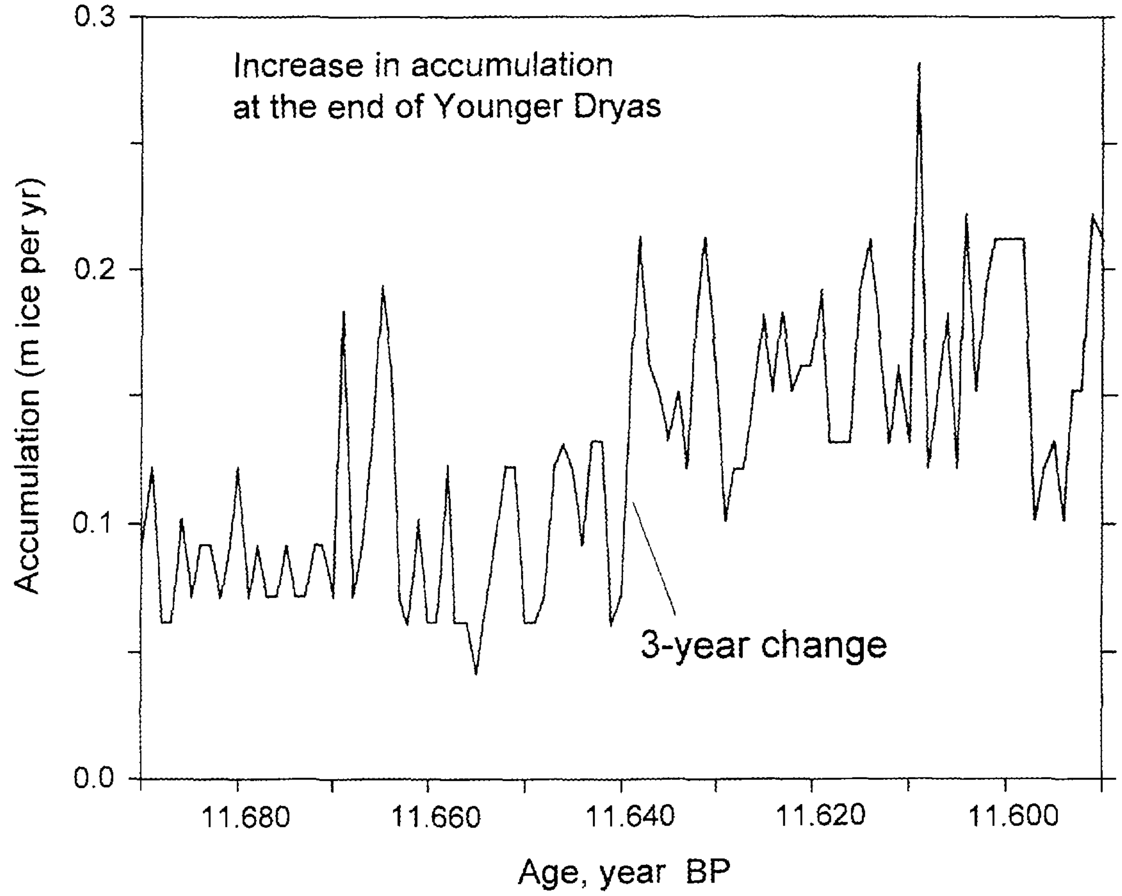

Figure 2-8. *At the end of the cold Younger Dryas event the precipitation recorded in the GISP2 ice core increased from around 0.08 m/yr to 0.15 m/yr in a few years. During approximately the same period the temperature increased by 10°C. From Alley* et al., *1993.*

follows temperature) are reported to have taken place within less than 50 years (Alley *et al.*, 1993; Taylor *et al.*, 1997). The majority of these changes occurs within less than 10 years. At the end of Younger Dryas the precipitation more than doubled in 10 years and temperature increased by about 5–10°C (Fig. 2-8).

Frequent, rapid and considerable variability of climate is particularly obvious in the Greenland ^{18}O record of the last glaciation (Dansgaard *et al.*, 1984; Heinrich, 1988; Broecker *et al.*, 1992; Bond *et al.*, 1993; Johnsen *et al.*, 1995). During most of the period, from 75 to 10 ka BP, temperature fluctuations with amplitudes of between -5 and –20°C, occurred every few thousand years. Even before 75 ka BP rapid fluctuations occurred and some appear also during the Eemian interglacial (Woillard and Mook, 1982; Thouveny *et al.*, 1994). These rapid fluctuations are named "Dansgaard-Oeschger cycles" (Fig. 2-9). The type of temperature fluctuations are now also recognised in deep-sea sediments covering glacial as well as non-glacial times between 500 and 340 ka BP (Bond *et al.*, 1997; Oppo *et al.*, 1998) and in low latitude monsoonal variability (Schulz *et al.*, 1998). The variability is therefore believed to be a typical component of the climate and is strongly influenced by a common forcing factor.

Other rapid fluctuations in climate are known from studies of North Atlantic deep-sea cores. One of these is the so-called Heinrich event, i.e. certain cold events with sea-

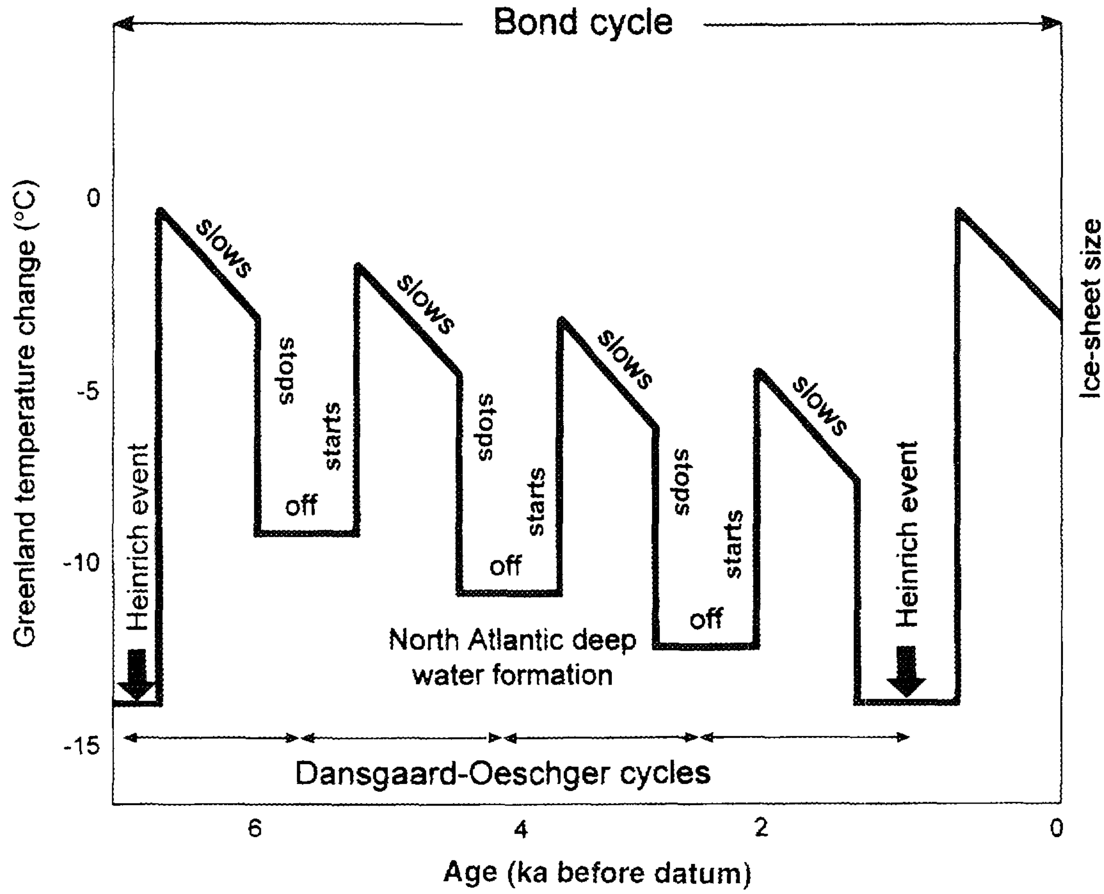

Figure 2-9. The Pleistocene climate has fluctuated frequently and rapidly at several time scales. The "Bond cycle" encompass several shorter cycles, the "Dansgaard-Oeschger cycles". At a few particularly cool periods distinct amounts of ice-rafted coarse debris were deposited over much of the North Atlantic area. These particular events are named "Heinrich events". So far six Henrich events have been identified and the upper five of these are dated to around 15, 20, 27, 40 and 50 ka BP. After Alley, 1998.

surface temperature drops of 2–6°C, within a few of the Dansgaard-Oeschger cycle (Fig. 2-9). At these events, of which six are recognised for the period between 70 and 14 ka BP, the amount of ice rafted minerogenic debris increases dramatically in the sediments (Heinrich, 1988; Broecker *et al.*, 1992; Bond *et al.*, 1992; Bond and Lotti, 1995).

Rapid changes in climate seem to be a natural component associated with times of climate changing conditions. The forcing leading to these abrupt events is unknown, but it could be related to changes in the North Atlantic deep-water formation. The Heinrich events are believed to be the results of major discharges of ice-bergs (surges) of the Laurentide or the Fennoscandian-Greenland ice-sheets.

2.3 Global synchrony

The global synchrony of major changes in climate is discussed widely (Bender *et al.*, 1994; Denton and Hendy, 1994; Jouzel, 1994; Lowell *et al.*, 1995; Sirocko *et al.*, 1996; Hughen *et al.*, 1998; Severinghaus *et al.*, 1998). Variations in incoming radiation affect the hemispheres differently, hence neither a global or a regional synchrony is to be expected.

However, it seems that, although regions respond differently to climate changes, there is a global synchrony in time of response and it is consistently found that major changes take place at the same time in the Arctic, the Antarctic and the oceans (Fig. 2-7). The difference between the Arctic and the Antarctic is considered to be less than 200 years for major changes in climate (Stauffer *et al.*, 1998). It is probable that the feedback effect of major ice sheets on the Northern Hemisphere (large ice-sheets mean increased albedo and increased cooling) has been large enough to dominate over the effect of varying hemispheric incoming radiation. This does not exclude that limited areas, because of local effects, or the independent timing of irradiation peaks, caused by precession and eccentricity (2.4.1), may have experienced a certain lead or lag for some climate events (Crowley and Kim, 1994). One such area may be south-western USA, where well dated carbonate deposits in the Devil Hole indicate an early Eemian warming compared with global conditions recorded in deep sea sediments (Winograd *et al.*, 1992).

For less long-lasting changes (e.g. lasting a few thousand years), as the observed rapid climatic events during the last glaciation, Greenland and Antarctica seem to have changed oppositely (Alley and Bender, 1998) or climate changes of Antarctica seem to lead Greenland climate changes (Blunier *et al.*, 1998). The reason for this should be that changes in the oceanic circulation lead to that the conveyor (2.4.3) cools the south at the same time it warms the north. However, the evidence for an out of phase situation is controversial (Steig *et al.*, 1998).

2.4 Forcing factors and feed-backs

While the orbital parameters are considered the main forcing factors of long term changes in climate, the documented global synchrony is believed to be a result of the feedback of major ice-sheet formation on the Northern Hemisphere. Several other factors found to change in the same pattern as the climate may also play a role as driving factors. To be able to determine whether these factors are primary driving forces of climate changes, or a secondary feedback effect, it is of fundamental importance to understand the existence of leads and lags between changes in climate and changes in the factors. This is still far from well elucidated.

2.4.1 The Milankovitch theory

In the late 1800s, James Croll first predicted the existence of a pattern of global changes in the climate, including a cycle of around 100 ka (Imbrie and Imbrie, 1979). The prediction, based on calculations, inferred variations in the seasonal distribution and amount of solar radiation reaching the earth as a result of changes in orbital parameters. Milutin Milankovitch (1879–1958), a Serbian astronomer and mathematician, elaborated the theory, which later became named after him. The orbital parameters included in the Milankovitch theory are considered the main forcing factors of long term changes in climate.

The seasonal distribution and amount of irradiation at the earth varies basically with three parameters, the eccentricity, obliquity (tilt) and the precession (Fig. 2-10):

1. The eccentricity of the ellipse that the earth follows around the sun varies. The periodicity is regarded as being around 100 ka long (Crowley and North, 1991; around 95.8 ka according to Bradley, 1985, 103 ka according to Alley and Bender, 1998). In addition a cycle of 413 ka has been identified (Crowley and North, 1991).

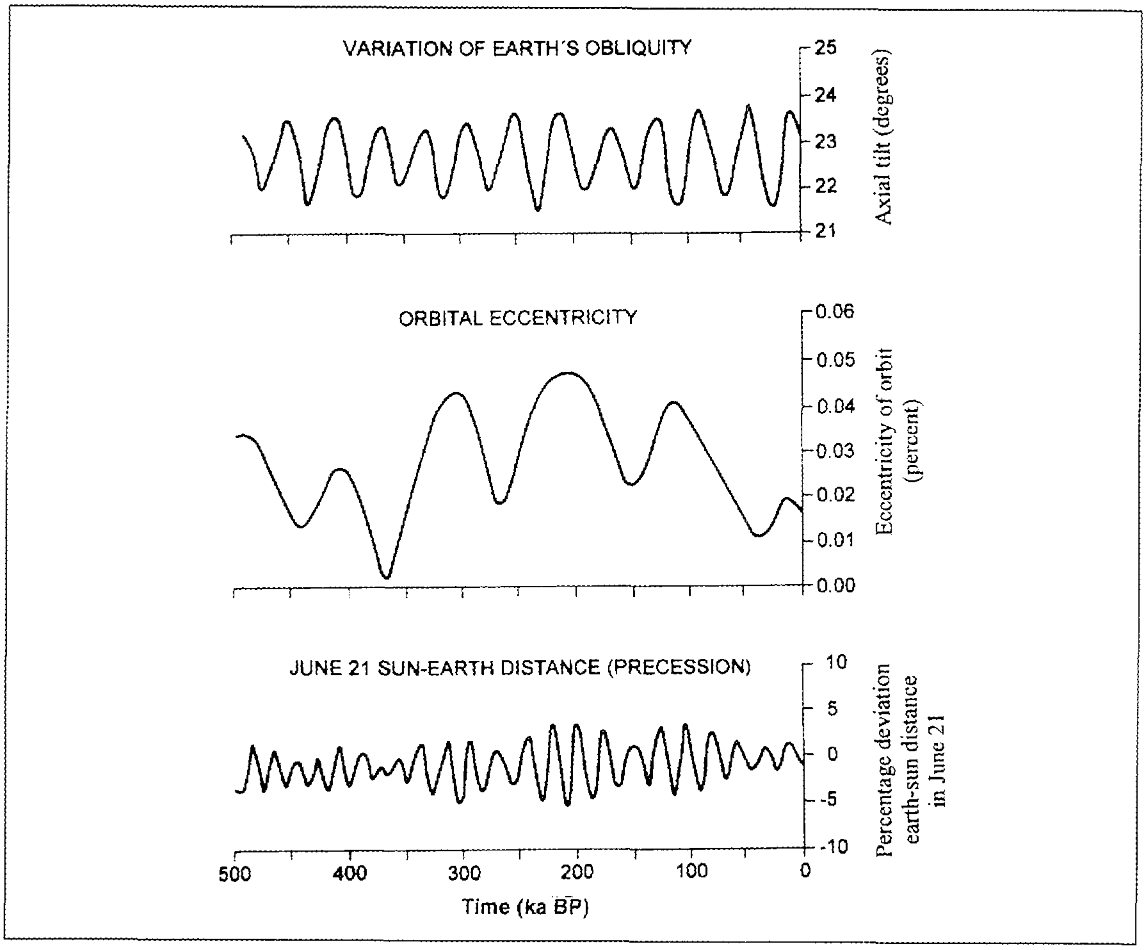

Figure 2-10. *Long-term changes in the global climate is believed to depend on the eccentricity, the obliquity and the precession. From Henderson-Sellers and Robinson, 1986.*

The eccentricity is at present low (Henderson-Sellers and Robinson, 1986). The total effect of variations in eccentricity is a change in solar insolation of maximum 0.2% at the top of the atmosphere. This will at the surface of the earth affect the temperature by maximum 0.5°C only (Crowley and North, 1991).

2. Variations in the earth's obliquity. The length of the cycle is about 41 ka. The tilt of the earth's axis varies between 21.8° and 24.4°. It is at present 23.5° and it moves towards less tilt. Low tilt reduces the temperature contrast between summer and winter and reduces the amount of irradiation reaching the poles and therefore favours glaciation (Bradley, 1985). High tilt can cause a difference of up to a maximum of 3-4°C increase near the poles at the same time as the tropics cool by 0.5°C (Crowley and North, 1991). The total amount of heat received by the earth does not change.

3. Precession (or June 21 distance to the sun). The distance between Northern Hemisphere/Southern Hemisphere and sun at Northern Hemisphere/Southern Hemisphere summer varies with three frequencies, which in average has a periodicity of 21.7 ka (23.7 ka, 22.4 ka and 19 ka) (Bradley, 1985). This cycle has no effect on the total amount of irradiation received by the earth but on seasonal contrasts. At present the Northern Hemisphere-sun distance is at its minimum in late December, which means that the Northern Hemisphere summers are cool. When the earth is close to the sun in the Northern Hemisphere summer, as it was at the end of the last

glaciation about 13 ka ago, the precession caused relatively warm Northern Hemisphere summer temperature and cooler summers on the Southern Hemisphere. Such conditions are unfavourable for glaciations. The effect on surface summer temperature can be a warming of the Northern Hemisphere of +10°C at the same time as the Southern Hemisphere is cooled by –6°C (Crowley and North, 1991).

The 100 ka cycle is believed to initiate the changes from interglacial to glacial conditions although the physical mechanisms behind are poorly understood and the global temperature effect of the eccentricity cycle is small. Field data do show a regularity of around 100 ka for a glacial cycle, but it should be remembered that the inter-glacial/glacial time-scale is not constructed independently but is tuned to fit the 100 ka eccentricity cycle. The effect of the 41 ka cycle and the 22 ka cycle are known from interstadials. Considerable amount of the irradiation changes only affects the contrast between the hemispheres and not the total amount of irradiation received. Because glaciations occurred at both hemispheres at the same time (Jouzel, 1994), it is accepted that a glaciation on the Northern Hemisphere, with its large land masses which can support major ice sheets, affect the global albedo and this way has a feed-back effect on the global climate. This feedback is large enough to force even the Southern Hemisphere into glaciations at the same time as the Northern Hemisphere is cold (Crowley and North, 1991).

The Milankovitch theory is basically accepted as the main cause of climatic changes. However, there are problems in the understanding of the theory. One of the these is the transition in the middle Pleistocene (about 0.9 Ma) seen in $\delta^{18}O$ deep-sea records from relatively low-amplitude, high frequency (41 ka) to high-amplitude, low frequency (100 ka) ice volume variations under essentially the same orbital forcing (Clark and Polland, 1998). The reason for this change is unknown, but the 413 ka periodicity in the eccentricity and other unknown changes may be of importance. One of these suggestions involves changes in the inclination of earth's orbit relative to the plane of the solar system (Muller and MacDonald, 1997). These orbital shifts would periodically dip earth into a climate-altering cosmic dust cloud. The theory has so far gained little support (Kerr, 1997).

Another critical view on the 100 ka eccentricity cycle as being the main forcing factor of glacial cycles is based on a calcite deposit in a water-filled crevasse in western USA. This site, called the Devils Hole, has provided several calcite cores up to 36 cm long, and $\delta^{18}O$ measurements show variations similar to the one known from SPECMAP[6] (Winograd *et al.*, 1992). However, the Devils Hole $\delta^{18}O$ record shows a trend over the last 450 ka not seen in the SPECMAP record. Most important for the discussion, the Devils Hole record places the beginning of the Eemian warming at 140 ka BP instead of 128 ka BP as SPECMAP record indicates (Winograd *et al.*, 1992; Kerr, 1997). If the Devils Hole record is correct and represents global conditions, deglaciation started before the Milankovitch cycles caused major warming. The opinion is refuted by Imbrie *et al.* (1993), but the results from Devils Hole may, according to Crowley and Kim (1994) after all reflect a beginning of the deglaciation leading into the Eemian interglacial. Modelling made by them indicate that the temperature at high latitudes were 1.0–1.5°C warmer than present already at 134 ka BP (Crowley and Kim, 1994). Dating of raised corals and submerged speleothems is one way to directly measure high and low sea-level stands and is considered an important option to further test the orbital theory as a climate forcing factor (Gallup *et al.*, 1994; Richards *et al.*, 1994; Szabo *et al.*, 1994).

[6] SPECMAP stands for Spectral Mapping Project.

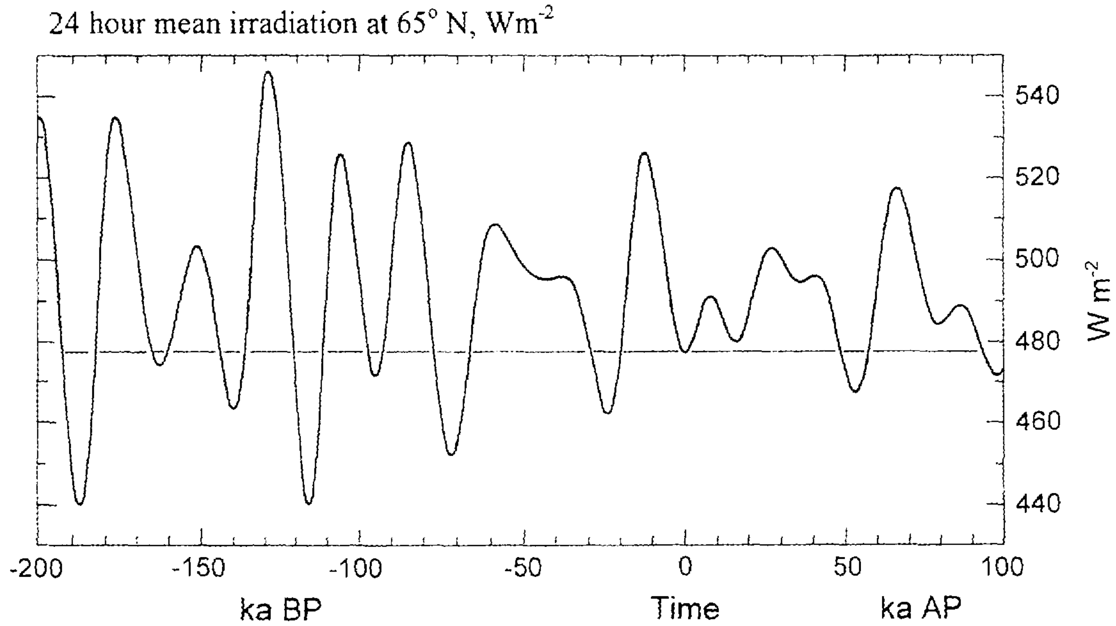

Figure 2-11. *The Milankovitch cycles have caused changes in the June 65 °N irradiation of about 100 Wm^{-2}. Next period of low irradiation will occur in about 50 ka. From Berger, 1994.*

Variations in the radiance balance caused by the Milankovitch cycles depend on three cycles of different length. Because of the interactions between the cycles, the effect on climate will vary with time and space in a complicated pattern. For example, it is virtually impossible to find an analogue to our present interglacial in the geological record. Recently Berger (1994) presented a detailed calculation for the last 200 ka and the future 100 ka (Fig. 2-11). This calculation, performed for 65°N and the month of June, shows that the amplitude between the maxima and minima in received irradiation during 24 hours, can vary with up to about 100 Wm^{-2}.

2.4.2 Greenhouse effect as a positive feed-back mechanism

The Antarctic ice cores demonstrate a clear correlation between temperature, CO_2 and methane (Chappellaz *et al.*, 1990; Jouzel *et al.*, 1993) (Fig. 2-12). The climatic effect of the changes in the atmospheric content has been suggested a possible cause of major amplification of the orbital parameters leading to a doubling of the effect (Vostok Project Members, 1995). A much smaller effect is suggested by Brocker and Denton (1990), who found that the effect of the added CO_2 could be at the most about 2°C and for methane a few 1/10 of one °C. Others (e.g. Carlowicz, 1996) object to the opinion that methane has such a small impact. Methane concentration in the atmosphere increased during each interstadial event (Alley and Bender, 1998). This increase may be an effect of increased precipitation in tropical areas (2.1.2) and is therefore a feed-back effect of changes in climate.

The Vostok ice core has provided a possibility to test the eventual lead or lag between temperature changes and changes in greenhouse gases, because the temperature-data (obtained from the $\delta^{18}O$-record) and the CO_2-data are provided from the same sections of ice. In the ice-core records, the temperature appears to have increased before an increase

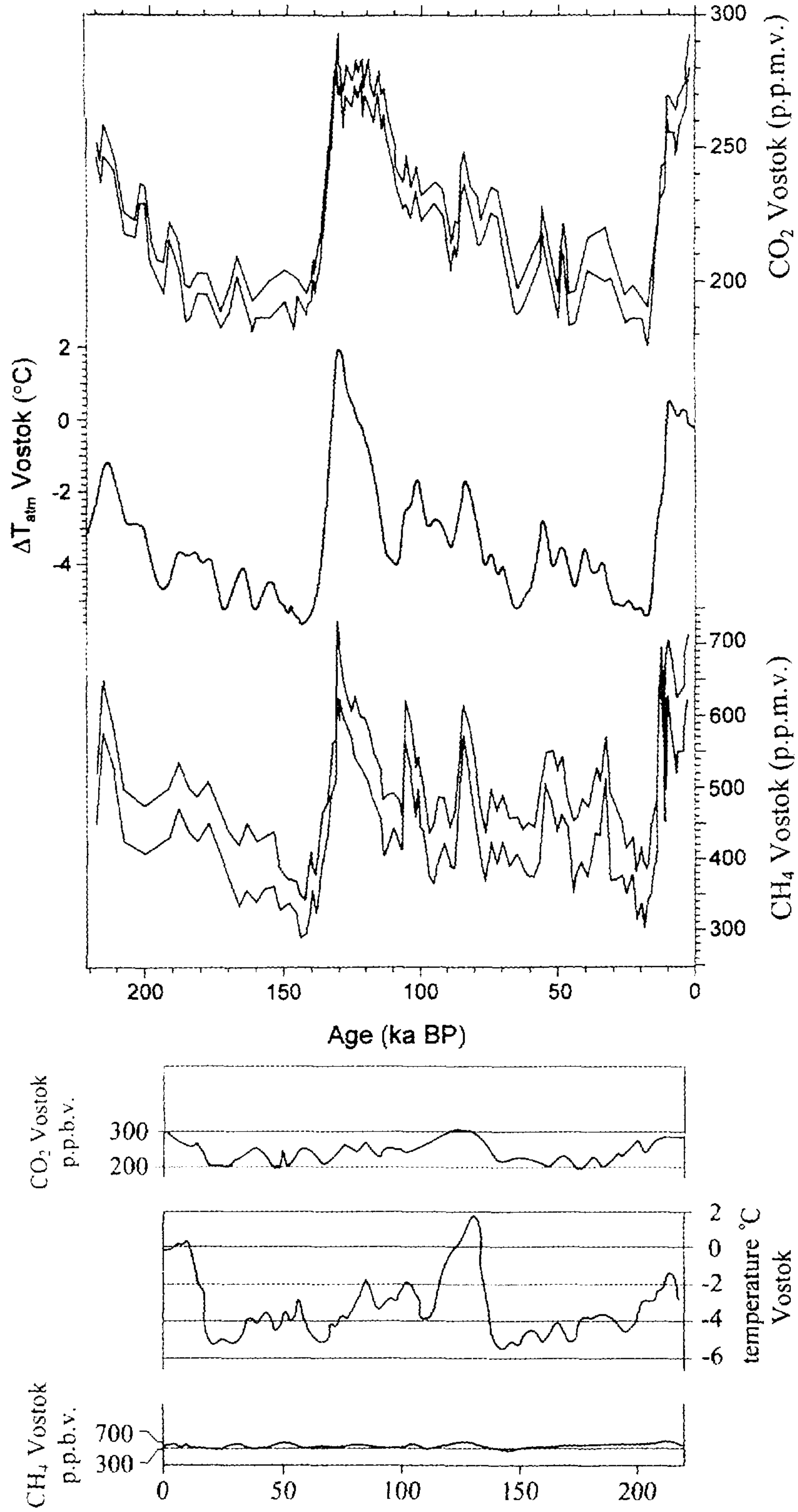

Figure 2-12. *The correlation between CO_2, CH_4 and temperature at Vostok is obvious (above). The increase in concentration of greenhouse gases explains some of the changes in temperature. However, according to Broecker and Denton (1990) the temperature effect of the change in CO_2 is not more than about 2°C and the effect of the change in CH_4 is only a few tenths of a °C. Therefore, the effect of these greenhouse gases in relation to the total change in temperature at Vostok is small (below).*

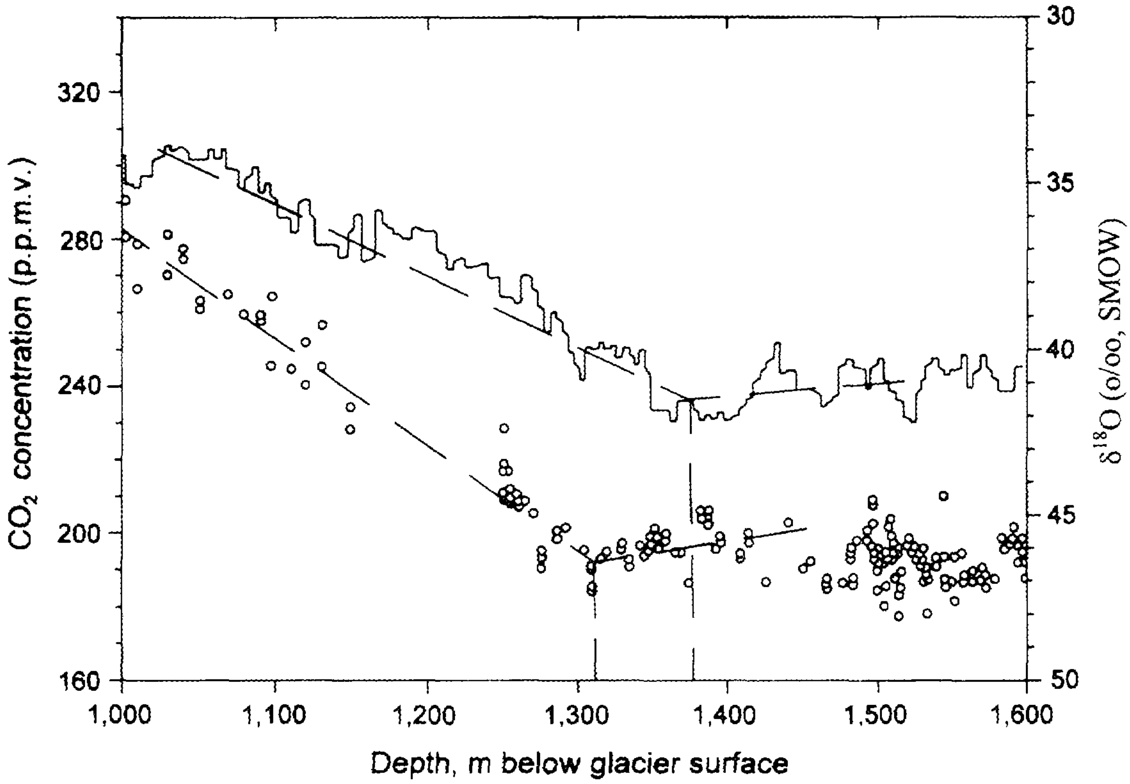

Figure 2-13. The marked change in temperature at the end of the last glaciation, as observed in the $\delta^{18}O$ record (solid line) in an ice-core from Byrd Station appears at a depth 60 m below the point where the CO_2 concentration (circles) increases. From Neftel et al., *1988.*

in the CO_2 occurred and CO_2 concentrations remained high after the temperature began to decrease (Fig. 2-13), indicating that CO_2 concentration in the atmosphere is a result of changes in climate and not the driving force (Jouzel *et al.*, 1993; Neftel *et al.*, 1988).

The importance of water vapour as a feedback mechanism is debated (Carlowicz, 1996; Broecker, 1997). Water vapour is the most abundant and efficient greenhouse gas. A reduction in temperature leads to a reduction in atmospheric water vapour. Reduced water vapour in turn causes further reduction in temperatures. Broecker (1997a) suggests that a 30% reduction in water vapour could change global temperature with 5–6°C (e.g. same figure as the suggested global temperature lowering at the last glacial maximum). Documented variations in the $\delta^{18}O$, of -8‰ in ice cores from the Andes, are believed to indicate a reduction of about 20% of water vapour content of the Late Pleistocene atmosphere compare to today's value. Such a reduction of the earth's dominant greenhouse gas is sufficient to account for a 3.5±1.5°C cooling of the tropical ocean surface during glacial times (Broecker, 1997a).

2.4.3 The thermohaline circulation

Since Broecker introduced the concept of thermohaline circulation or "the conveyor belt theory", this process has frequently been regarded as central for the global climate (Broecker and Denton, 1990; Broecker, 1997b; Driscoll and Haug, 1998). The theory is based on the idea that the North Atlantic current is largely a result of deep water formation in the North Atlantic area. During winters, cooling of the highly saline surface water results in increased density and the water sinks. When it sinks, relatively warm water from south-west replaces the sunken water. An increased global temperature could reduce the cooling to a point when the density increase becomes too small to cause sinking of the surface water and hence a reduced transport of warm water to the north-east. Another possible factor reducing deep-water formation could be increased non-saline water from e.g. melting icebergs (Broecker, 1994). This would lead to a reduced salinity, which leads to increased amount of drift ice and reduced cooling during winters. The expanded ice cover in the North Atlantic would protect the water from cooling. The existence of coarse grained layers in deep sea sediments from the glacier times is interpreted as an indication of massive discharge of ice bergs which could have reduced salinity (Bond *et al.*, 1997).

2.4.4 Solar forcing

The atmospheric concentration of the three isotopes ^{10}Be, ^{14}C and ^{36}Cl have been found to vary considerably during the period of major climatic changes during Late Pleistocene. All three isotopes are produced through cosmic rays and this radiation depends on solar modulation of the global magnetic shield. The concentration in the atmosphere of these isotopes therefore can be modulated by solar activity.

The concentration of ^{10}Be in the Antarctica ice core closely follows the $\delta^{18}O$ variations during the last 150 ka (Fig. 2-14). The increase in the ^{10}Be concentration during

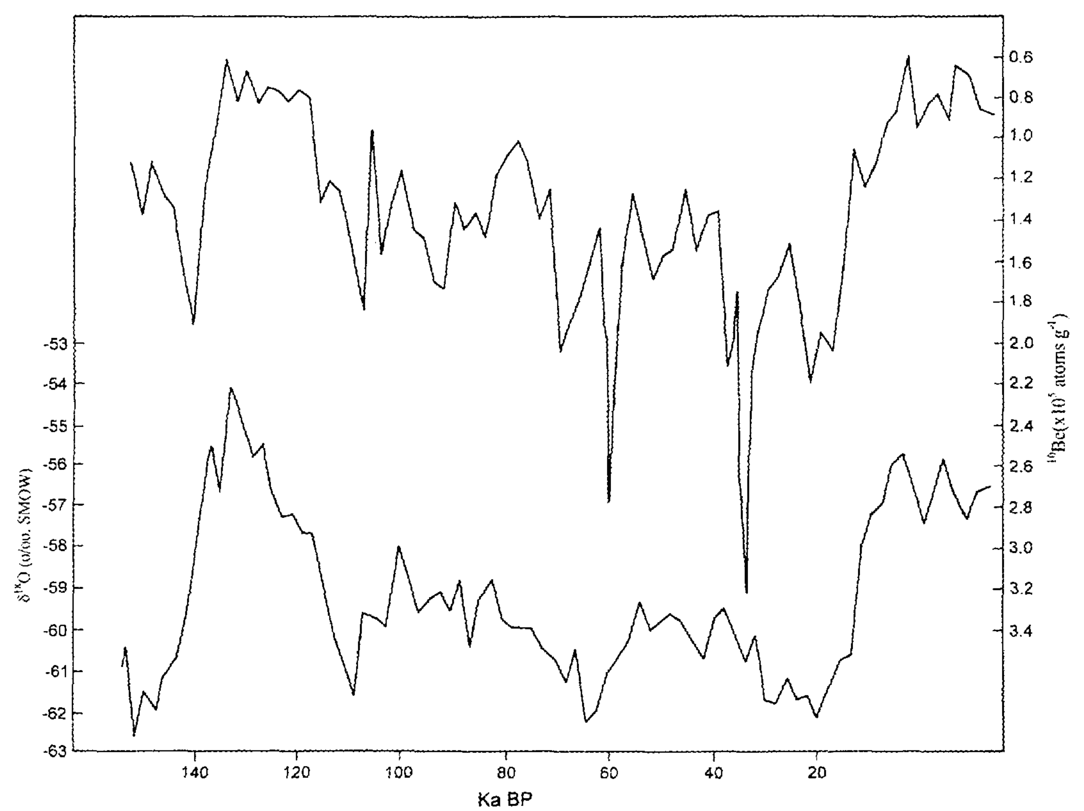

***Figure 2-14.** Changes in temperature at Vostok 150 ka to the present and variations in ^{10}Be. From Raisbeck* et al., *1987.*

Pleistocene was first suggested to be a result of decreased precipitation (Raisbeck *et al.*, 1987), but recent studies indicate that at least the peak at 35 ka BP may have been caused by a higher production rate of cosmogenic radionuclides rather than by reduced precipitation (Beer *et al.*, 1992).

The discovery of a lake in Japan with a very long sequence of annually layered sediments has, through ^{14}C-dating of the sediments, permitted the reconstruction of variations in the ^{14}C concentration in the atmosphere back to 45 ka BP (Kitagawa and van der Plicht, 1998). The authors propose two explanations to the variations:

(i) major changes in solar radiation which directly affects the ^{14}C production in the atmosphere;

(ii) dilution of the atmospheric ^{14}C content of the atmosphere through degassing of ocean water.

The latter explanation is favoured.

Another recent study deals with the ^{36}Cl flux in the GRIP ice core (Baumgartner *et al.*, 1998). A peak in ^{36}Cl concentration around 38 ka ago coincides closely with one major fluctuation in the ^{14}C and the ^{10}Be concentration. The ^{36}Cl production depends on variations in the dipole strength or on solar modulation of the earth magnetic field.

It is apparent that the atmospheric content of the isotopes ^{10}Be, ^{14}C and ^{36}Cl can change as a result of variations in solar radiation and/or of a second factor; for ^{10}Be it is precipitation, for ^{14}C it is the reservoir effect and for ^{36}Cl it is the dipole field. A majority of previous studies favour the second factor as causing the isotopic changes. However, it can not be excluded that variations in solar radiation have caused the isotopic fluctuations and then also affected climate. This possibility definitely deserves more attention in future studies.

2.4.5 Dust and volcanoes

The concentration of dust in ice cores from Greenland and Antarctica varies distinctly with time (Hammer *et al.*, 1985, Broecker and Denton, 1990). Because the concentration is large during ice ages, possible climatic impact has been discussed. Antarctic dust is believed to mainly originate from the dry areas of the southern continents and the, during ice ages, exposed shelves surrounding these (Petit *et al.*, 1990). Ice cores from Vostok and Dome Circe reveal that the atmosphere during glacial time transported more dust than today (Broecker and Denton, 1990) and major peaks in dust are dated to around 150 ka BP, 70 ka BP and a double peak at 20 and 15 ka BP (De Angelis *et al.*, 1987). Most of this dust is of terrestrial origin and is believed to be a result of general increased atmospheric circulation.

Major volcanic eruptions are also known to affect climate (Sear *et al.*, 1987), and even a possible volcanic effect on the climate of the last 40 ka has been suggested (Bryson and Goodman, 1980). Volcanic eruptions emit large quantities of sulphur-rich gases to the atmosphere, which can lead to a reduction in temperatures under a few years after the eruption. In addition to the potential of eruptions to modify climate, it is believed that rapid climate changes can enhance crustal stresses, thereby leading to increased volcanic activity (Rampino *et al.*, 1979; Zielinski, 1998). Low sea levels and low temperatures are associated with major volcanic eruptions at around 120 and 74 ka BP (Toba eruption; Rampino and Self, 1993) and at 11 ka BP (Linsley, 1996).

Even extraterrestrial dust may have an influence on climate (Farley and Patterson, 1995; Muller and MacDonald, 1997). The idea posited is that the "inclination of the earth's orbital plane" would lead to that extraterrestrial dust clouds enter the earth with a periodicity of around 100 ka.

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3 The Holocene

The Holocene includes the period following on the last deglaciation i.e. the last 10 ka. This period has had a relatively stable climate (Dansgaard *et al.*, 1993; Broecker, 1994; Alley and Bender, 1998). However, even if no drastic changes like those known from Eem and the last glaciation are evident, the general pattern includes low amplitude fluctuations superimposed on a slow but steady trend towards cooler climate. This trend, known from the Greenland ice cores (Johnsen *et al.*, 1995), from pollen records (Woillard and Mook, 1982) and from lake levels in tropical areas (Stager *et al.*, 1997), is likely to at least partly be a result of orbital forcing (Kutzbach and Street-Perrot, 1985). The seasonal cycle of solar radiation was considerably amplified in Northern Hemisphere between 15 and 6 ka BP because the perihelion occurred in the northern summer (it now occurs in northern winter) and because of the axial tilt was almost 1° larger than today. At the time of maximum amplification, at 11–10 ka BP, the daily mean irradiation was about 30 Wm^{-2} (7%) greater than today in July, and about 25 Wm^{-2} less in January. These changes in seasonal solar radiation were larger than the forcing perturbations typically used in sensitivity experiments (a doubling of atmospheric CO_2 correspond to a 4 Wm^{-2} change in the radiate heating at the earth's surface).

3.1 Patterns

3.1.1 The Holocene, a short warm period between long cold glaciations

The general pattern during the Holocene is the same as it is for glacial/interglacial cycles: rapid warming and a slow cooling. The magnitude of the interglacial temperature is surprisingly even, but the details superimposed can vary. The present temperature at Vostok is between 1 and 0.5°C lower than it was at the beginning of Holocene and this Early Holocene maximum temperature was 1.5°C lower than it was at the maximum of the previous interglacial, the Eemian period (Jouzel *et al.*, 1993). Only for the last two warm periods are a relatively detailed record available (Greenland Ice-core Project Members, 1993).

There is no single period as stable as Holocene in the last 160 ka (Dansgaard *et al.*, 1993; Broecker, 1994). In opposite to the Holocene, climate fluctuated distinctly during Eem, the previous warm period before the last glaciation, Weichsel (Fig. 1-1). Between about 135 ka and 117 ka BP six distinct temperature peaks are recorded when the temperature was as warm or warmer than during Holocene. Between these peaks the temperature dropped approximately as much as during the Younger Dryas, or with about 10°C. The fluctuations in temperature became even more dramatic during Lower Weichsel.

In addition to a slight cooling during the 10 ka of the Holocene period, there are temperature and precipitation variations known from the Greenland ice cores (Meese *et al.*, 1994; Alley *et al.*, 1997), glacier fluctuations in mountain areas (e.g. Karlén and Kuylenstierna, 1996), variations in African lake levels (Nicholson, 1980; Stager *et al.*, 1997) and from speleothem deposition (Holmgren *et al.*, 1998; Holmgren *et al.*, under review; Lauritzen and Lundberg, 1998). The amplitude of these fluctuations in temperature is of the order of 1–2°C, except for at 8200 cal yr BP, when the temperature was reduced considerably (Alley *et al.*, 1997).

A number of frequencies of variations in temperature and rainfall have been discussed (Bond *et al.*, 1997) but only a few of these suggested periods are commonly found. One of these is a period around 1500 year long and which is believed to have the same origin as the Dansgaard-Oeschger fluctuations well known from Greenland ice cores (Dansgaard *et al.*, 1984; O'Brien *et al.*, 1995; Bond *et al.*, 1997).

Temperature records of the last 400 years

Discussions about global temperature is mostly based on the estimate of global temperature since the late 1800s, published by WMO (1996) and in numerous other publications. No global temperature based on observations can be produced for the period before about 1850, because there are too few observations. The observations from the 1900s show that when global temperature increased between 1920 and 1940, there were still large areas in the world where the temperature was stable or even decreased (Pittok, 1978). With a change in climate follows changes in circulation patterns. A change may lead to decreased temperature in restricted areas even if the global temperature increases (Briffa *et al.*, 1998).

The first regular instrumental observations of temperature were initiated in England in 1659 (Manley, 1974) and other series of observation began in the early 1700s (Moberg and Bergström, 1997). These long temperature series are few and are all located in Western Europe. The trends of these series all indicate that the temperature fluctuated during the 1700s and early 1800s and at some occasions were similar to the temperature experienced during the 1900s, but the temperature was in average for the early period slightly lower than during the 1900s.

While these early temperature observations are too few to reveal global temperature for the period before 1850, a combination of different paleorecords, such as dendrochronology, ice-core studies, diary studies, cave deposits and glacier fluctuations, have provided information enough to permit a reconstruction of a Northern Hemisphere summer temperature for the last 400 years (Bradley and Jones, 1993). A reconstruction of Arctic temperatures for the same period confirms the Bradley and Jones reconstruction, but shows larger amplitude in temperature change (Overpeck *et al.*, 1997). Both records show that the temperature was low during the 1600s, increased up to the early 1800s and then dropped rapidly. A minimum was reached just before the so-called "global record" begins around 1850. The maximum was reached around 1940 and thereafter the Northern Hemisphere and Arctic temperature decreased up to the mid 1970s, when a new increase begun. The Arctic temperature and, according to a recent dendrochronological study (Briffa *et al.*, 1998), also the Northern Hemisphere summer temperatures are lower than in the 1940s. For the whole globe, however, the temperature is now slightly warmer than in 1940.

The last 1000 years

Information about temperature changes during the last 1000 years is obtained from denrochronological studies at a moderate number of localities (e.g. LaMarche, 1974; Briffa *et al.*, 1992; Briffa *et al.*, 1995; Luckman *et al.*, 1997). Major changes in the temperature, such as the relatively warm climate during the 1100s, the 1400s and 1500s and low temperature during the 1600s and early 1700s, are recognised in several records from both hemispheres. Even details are similar between some regions, e.g. Scandinavia and the Rocky Mountains. Because of the circumpolar circulation and position in relation to the upper-air, so-called, Rossby waves, areas have a tendency to be in or out of phase. Rossby waves is the term used for the boundary between arctic and polar air masses. The boundary usually have the form of 3-4 waves of varying amplitude around the globe and are strongest at the Northern Hemisphere. The waves can be stationary for several weeks, but normally migrate slowly in a west to east direction. Average temperature for latitudinal zones can only be obtained by integration of area and anomaly temperature.

The last 10,000 years

Many studies of the Holocene climate are based on pollen records, which only reveal major changes in climate and the period has therefore been considered stable (Broecker, 1994). However, it is now recognised that even the Holocene climate experiences fluctuations of the same frequency, but of a lower amplitude, as the Dansgaard-Oeschger fluctuations during Pleistocene (Alley *et al.*, 1997; Bond, 1997) and which also have been observed for the period 500–340 ka BP (Oppo *et al.*, 1998). The similarity in frequency suggests that these climate oscillations may be caused by the same forcing, but one amplifying factor is missing during Holocene (Karlén and Kuylenstierna, 1996; Bond *et al.*, 1997).

Only a few high-resolution paleotemperature records, have yielded information about the whole Holocene. The most detailed of these are the Greenland $\delta^{18}O$ records. The variations in temperature during Holocene are small compared with the variations during the Pleistocene; the variations are believed to have been up to about 0.5°C (Cuffey *et al.*, 1995; Alley *et al.*, 1997) (Fig. 3-1). This is a low variation compared with estimates from other records, such as the alpine tree limit record for Scandinavia, which indicates Holocene temperature variations of 1 to 2°C (Karlén and Kuylenstierna, 1996). Temperature changes of 1.5–2.5°C and a 1,500 years periodicity are also inferred from a high-resolution (30 years resolution) isotopic record from a Norwegian speleothem (Lauritzen and Lundberg, 1998).

The similarity between several Holocene paleoclimatic records indicates that at least major changes may be global. However, several records differ distinctly. This may be because:

(i) there is no common forcing factor;

(ii) the dating is not good enough;

(iii) with changes in climate follow changes in circulation which may have local effects (e.g. orographic effects) not typical of the global climate.

Variations in climate lasting over several thousand years are observed in the salt content of ice-cores from Greenland (O'Brien *et al.*, 1995). These variations are considered to depend on large scale changes in the circulation. These variations in salt content occurred, in a broad sense, at the same time as major changes in the Scandinavian climate and several other localities. The time between the major events are roughly 2500 years, a period in climatic changes which also is observed in solar activity (see periodicity, 3.1.2).

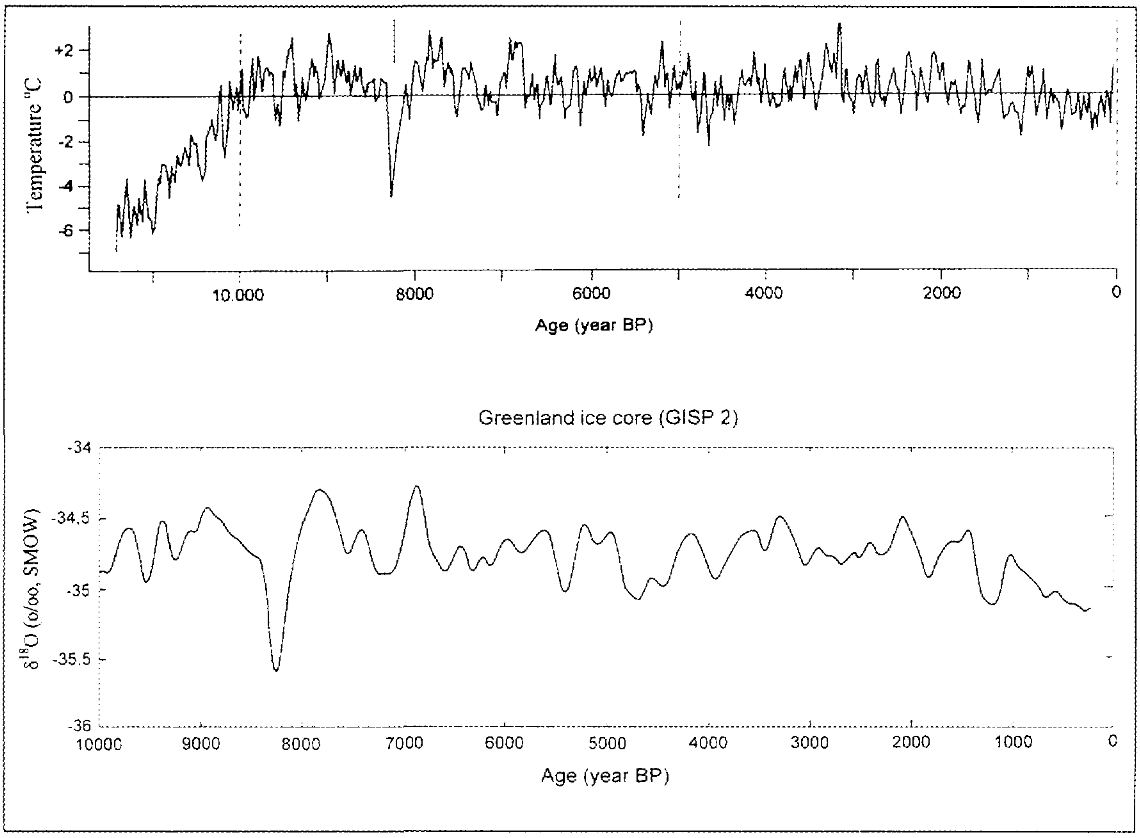

Figure 3-1. *Greenland temperature in relation to present conditions (above). The data is obtained from the GISP2 ice core (from Alley* et al., *1997). The lower panel shows the same record filtered (Gaussian filter) and with variation in climate presented in $\delta^{18}O$ (below).*

3.1.2 Periodicity

A tendency to periodicity in climate with cycle lengths varying from under a year up to 6000–7000 years has frequently been claimed. Few of these are caused by physical processes known and understood. In this context only a few of the most commonly found cycles will be mentioned.

One physical explanation to periodic changes in climate is changes in solar radiation. Recently, direct measurements from satellites demonstrate that solar radiation varies slightly with the variations in the sunspot cycle (Foukal, 1994). Several studies have revealed variations of around 2500 years in glacier fluctuations (e.g. Denton and Karlén, 1973), Greenland ice cores (Dansgaard *et al.*, 1971; 1984; Bray, 1971) and in deep-sea records (Pisias, 1973; Bond *et al.*, 1997). A fluctuation in solar activity of approximately the same length has been noted by Sonett and Finney (1990) and by Stuiver and Braziunas (1993). The same frequency is observed in paleorecords for the period 500 to 340 ka BP and is therefore believed to be a stable component of the climate (Oppo *et al.*, 1998). These variations, and several others, are also recognised in the atmospheric ^{14}C content. The concentration of ^{14}C varies with solar activity, thus supporting the hypothesis that this periodicity is likely to be caused by variations in solar radiation.

A quasi periodic fluctuation with a length of around 1500 years has been noted in several studies (Dansgaard *et al.*, 1984, ice-cores; Sirocko *et al.*, 1996, monsoon climate; Bond *et* *al.*, 1997, North Atlantic). Because no variation of this length is known from studies of solar influence on ^{14}C production in the atmosphere (Stuiver and Braziunas, 1993), Bond concludes that this frequency is not a result of solar variations. A similarity between glacier fluctuations and variations in the ^{14}C production in the atmosphere, however, made Wigley and Kelly (1990) discuss a possible link. Even if they found a significant correlation, the solar influence was not considered convincing. Karlén and Kuylenstierna (1996) have discussed the correlation between Scandinavian climate and the solar index, published by Wigley and Kelly, and found a good, but not simple linear correlation.

A study of dust concentration in a Late Pleistocene ice core from Greenland indicates an 11-year cycle (Ram *et al.*, 1997). The length of the cycle for minima varies between 8.9 and 14 years with an average of 11.1±1.3 years. It is suggested that the large variations in dust concentration is a result of variable amount of precipitation in the source area and that this is caused by variations in the distribution of precipitation.

3.1.3 Precipitation

There are several precipitation records covering the last 100 years or more, but their value is limited. The wind shielding of the instruments has been improved with time and this has had a marked effect on the amount of precipitation collected. Also, precipitation observations are very much affected by local conditions such as trees growing close to instrument installations (Eriksson, 1981).

In general terms, precipitation decrease with a decrease in temperature, e.g. low precipitation during glacial time (Broecker, 1997a). However, the circulation pattern is extremely important for the precipitation actually received at one station. With even small changes in global heat balance, changes in the average amplitude and wavelength of the Rossby waves is likely to occur. No clear pattern has been recognised so far, but the tendency of these kind of changes in circulation has been discussed (Parker, 1976). Also, a change in the north – south migration of the intertropical convergence zone (ITCZ) is likely to occur, which should affect long term changes in precipitation. Even ocean currents and changes in the intensity of these currents affect precipitation by regulating the amount of evaporation. El Niño is an extreme example on the oceanic influence on local as well as global precipitation pattern (WMO, 1987).

The 200 year long meteorological record from Stockholm has been compared with records from England (Eriksson, 1981). There is no obvious correlation between temperature and precipitation in Stockholm and there is neither any correlation between the Stockholm and England precipitation records. However, the temperature data for Stockholm and England are similar.

Many African lakes are known to have had relatively high water levels from around 10 ka BP and up to Mid Holocene (Nicholson, 1980; Stager *et al.*, 1997). The amount of methane in a Greenland ice core also indicate wet conditions during Early Holocene and dry conditions in Mid Holocene. The amount of methane has increased since around 5000 cal yr BP, which should indicate wetter conditions in the tropics. However, most records do not indicate water levels rising during the last 5000 years. A microfossil study of a lake in Burundi confirms the tendency to decreasing precipitation during the Holocene and only a brief period of wet conditions is recorded in the second half of the Holocene (Bonnefille *et al.*, 1990). Even during Early Holocene there were changes in precipitation. Archaeological studies in southern Egypt have revealed hyperarid periods dated to around 8000 cal yr BP and around 7500 cal yr BP (Malville *et al.*, 1998). Also, dryer climate appears to have begun at some time after 5500 cal yr BP. Slightly wetter climate around 9000, 7300, 6300 and 5500 cal yr BP is indicated by dates on archaeological sites.

A general reduced precipitation in tropical areas during the Holocene is also found by Hodell *et al.* (1995) for Central America. Precipitation appear to have been large during Early Holocene. After 5000 cal yr BP the precipitation diminished slightly and a major drying trend begun after 3000 cal yr BP. Probably, the correlation between methane and precipitation in tropical areas suggested by Blunier *et al.* (1995) is not valid for late Holocene.

The precipitation over Greenland is known from calculation of annual accumulation in ice-cores studies (Meese *et al.*, 1994). The accumulation rose rapidly up to about 9000 cal yr BP and has since then fluctuated relatively little. However, a distinct minimum occurred at the time of the 8200 cal yr BP cold event and the precipitation was slightly lower than during most of Holocene between about 7000 and 5000 cal yr BP.

3.1.4 Sea-level

Sea level changes during Holocene are well known for several areas with a marked land uplift, such as Scandinavia and North America (Fairbridge and Hillarie-Marcel, 1977; Svensson, 1991; Påsse, 1997). Changes in sea level in these areas are observed as a series of beach ridges believed to be formed, either by major storms ("storm-beaches"), or by the erosion effect of sea during a period of equal land uplift and sea level rise.

During Early Holocene the sea level rose rapidly because of melting of remnants of ice-sheets. The sea-level rise was reduced in the Mid Holocene (about 4000–5000 cal yr BP) and has thereafter slowly become lower (Dawson *et al.*, 1998). Superimposed on this long term changes are variations of decades to century scale (Fairbanks, 1990; Bard *et al.*, 1996).

The cause of these short fluctuations must be:

(i) A direct response to changes in the mass balance[7] of the major ice sheets of Antarctica and Greenland. The mass balance of both these ice sheets is close to 0 but it is not well established (Houghton *et al.*, 1990, p. 268). Glaciers and small ice caps are believed to have contributed with water enough to raise sea level by 2.8 cm during the last 100 years.

(ii) Thermal expansion of sea water. This is generally believed to be small because only surface water will be affected. For the period 1880 to the present the thermal expansion is estimated to between 2–6 cm (Houghton *et al.*, 1990, p. 267).

Detailed knowledge about the present behaviour of sea level is difficult to establish because most well maintained watermarks are located in major cites, where land is likely to sink because of the load of the constructions. However, the consensus of extensive studies reported in IPCC (Houghton *et al.*, 1990) is that the sea-level rise since 1880 is about 12 cm.

[7]The ice mass-balance is the sum of annual snow accumulation (winter precipitation) and ablation (summer melting). For Antarctica the melting and freezing under shelf ice and the breaking off of icebergs are also taken into account.

3.2 Synchrony within the Holocene

As mentioned previously major changes in climate are synchronous in spite of that obliquity and precession should lead to asynchrony between the hemispheres. Less is known about the relatively moderate Holocene changes in climate recorded at a number of localities spread over the world. One major reason why it has been difficult to test global synchrony is that the dating is frequently based on a few ^{14}C dates and therefore not precise enough to permit accurate comparisons. Another reason is that changes in circulation pattern can cause localities to be out of phase (e.g. the Greenland "seesaw"; Lehman 1993). It is therefore necessary to integrate area and temperature before a firm conclusion can be made.

Most studies of the Holocene climate are focused on the climate of limited areas, but there are a number of studies in which a global synthesis is attempted. In 1986 Röthlisberger published his results from studies of glacier fluctuations at a number of sites well spread over the world. His conclusions were that major variations in climate lasting several hundred to a thousand years were global. His evidence was obtained from high alpine areas and it was therefore suggested that the climatic change not necessarily also occurred in non-glacial areas. Grove (1988) agreed that the last major cool period, the so called Little Ice Age, and following glacier retreat beginning in the 1800s was global in its extent. However, she is of the opinion that it was not possible to conclude that earlier events of glacier expansion during the period before the Little Ice Age were of global extent. In a study of possible solar influence on climate, Wigley accept the existence of global changes (Wigley, 1989).

Several records indicate synchrony or close to synchrony. One example is the similarity between dendrochronologies from northern Sweden and the Rockies (Briffa *et al.*, 1992; Luckman, 1997). Another example is a close relationship in time for changes in the Scandinavian Alpine tree-limit and the Greenland ice cores (Karlén and Kuylenstierna, 1996; Alley *et al.*, 1997). Even widely dispersed regions, as Greenland and Southern Africa show good correlation for the last 6000 years (Tyson *et al.*, 1997; Holmgren *et al.*, in press).

3.3 Possible processes

3.3.1 Solar forcing

Several studies of the recent climate have added support to the opinion that solar variability is an important factor for changes in climate on time-scales from less than a year and up. The global temperature is since 1965 calculated from radiosonde balloon observations and from 1978 also calculated by means of satellite observations. These two records are similar and the calculated temperature is also similar to the "global record" except for that the earth surface level temperature includes a trend towards warmer climate not seen in the other records (WMO, 1997). There are several large and rapid changes in the well-known record of the last decades of up to 0.8°C in 3 years, superimposed on small (approximately 0.2°C) sinusoidal fluctuations. El Niño – La Nina events and major volcanic eruptions, largely explain the large and rapid fluctuations. The sinusoidal change coincides closely with the 11 year sunspot cycles (Karlén, unpublished). Even if this sunspot link only is demonstrated for the last 30 years, it is an indication of a solar influence, an influence too week to be discovered in single records because of numerous factors affecting temperature.

Friis-Christensen and Lassen (1991) pointed out a clear correlation between the length of the 11 year solar cycle (varies between 9 and 12 years, in average about 11 year) and climate during the last 200 years. The correlation was tested by Kelly and Wigley (1992) who found the best statistical correlation between a climate model based on length of solar sunspot cycle. Models including greenhouse forcing was less well correlated with temperature. However, solar forcing was disregarded as a major factor because the authors considered the importance of greenhouse forcing could not be questioned. Further support for the solar forcing was found by Lean *et al.* (1995) and Soon *et al.* (1996), who recognised a good correlation between a climate reconstruction based on solar forcing and known temperature change during the last 400 years. Possibly, it is pointed out, that greenhouse gases have affected the temperature slightly during recent years. However, this conclusion is based on the earth surface level observations on which the "global record" is based. If the radiosonde and satellite temperature record is trusted (WMO, 1997), the greenhouse effect will be small.

Moreover, the variability is similar to the solar 11 year cycle observed also for other stars (Baliunas, 1993). Her conclusion is that stars appear to fluctuate with a periodicity of about 11 years. The amplitude of the cycle varies with time, but is considered to be of the same order as the variations observed to occur at our sun. Periodic behaviour of suns therefore appear to be the role and not an exception.

A study of $\delta^{18}O$ from Greenland and ^{14}C variations in dendrochronologically dated tree rings indicates a solar influence on climate during the last 1000 years (Stuiver *et al.*, 1997). The observed temperature change could be explained by a 0.3% change in the solar constant. Before 1000 BP the frequency of temperature changes recorded in the ice-cores are more frequent than expected from the solar variations derived from dendrochronology and ^{14}C dated tree rings. Stuiver *et al.* (1997) express that a significant correlation is absent, except for these last 1000 years.

Bond *et al.* (1997) have found relatively low amplitude fluctuations in the Holocene record of the North Atlantic, which are of similar duration as the Dansgaard-Oeschger events, and he suggest that these are caused by the same type of forcing even if the amplitude is smaller. Events of the same duration have also been observed in terrestrial records. Denton and Karlén (1973) observed that alpine glacier advances in several areas were separated by about 2500 years, a period later also observed in ice-cores from Greenland (Dansgaard *et al.*, 1984). A similarity between the timing of glacier advances and unusual high atmospheric concentration of ^{14}C made Denton and Karlén conclude that the forcing was variations in solar radiation. Wigley and Kelly (1990) studied the statistical correlation between the, at that time much improved knowledge about ^{14}C variations in the atmosphere and glacier advances, and found a statistical significant correlation. A renewed study by Karlén and Kuylenstierna (1996) has added support for the opinion.

3.3.2 Volcanic influence

Direct observations of global temperature before and after volcanic eruptions during recent years, show that the surface temperature has been reduced for a few years after these events (Sear *et al.*, 1987). At the same time, the temperature in the stratosphere has increased slightly (WMO, 1997). The solar radiation reaching the surface of the earth is reduced because some irradiation is absorbed and some reflected back to space by particles. Only eruptions that disperse considerable amounts of volcanic dust in the stratosphere have an impact on surface temperatures. While Mount Agung (1962), El

Chichon (1982) and Pinatubo (1990; Minnis *et al.*, 1993) had a distinct effect, other eruptions, such as St Helens in western USA 1980, spread dust mainly in the troposphere and therefore had little impact on climate (Robock, 1981).

Long term effects of volcanic eruptions have been discussed in a number of reports. Important steps towards an understanding were made when Lamb constructed a dust index for known volcanic eruptions (Lamb, 1970). The climatic effect of eruptions is limited to 1–3 years (Karl, 1993) and it is therefore only if eruptions occur frequently over long periods that these will have a major effect on climate. Detailed information about the last several hundred year shows that eruptions occurred frequently and therefore may have had an impact on the cooling during the Little Ice Age. There are two periods during the last few hundred years when no, or only a few, volcanic eruptions occurred (Bradley and Jones, 1992). The most distinct one of these periods coincides with the warming from about 1920–1940 and the other, less marked, occurred in the early 1700s, coinciding with another period of warming.

The Greenland ice cores have permitted the measurement of atmospheric acidity, which is of importance for aerosol formation (Hammer, 1977; Hammer *et al.*, 1980). An acidity index for Holocene, constructed by Zielinski *et al.* (1994), shows that the acidity was very high during much of Early Holocene, a period generally believed to have been relatively warm. The warm climate of this period is likely to have been a result of orbital forcing (Kutzbach and Street-Perrot, 1985) and it can not be excluded that the global temperature might have been even warmer if the volcanic eruptions had not cooled the climate. However, at present it is not possible to firmly conclude that volcanic eruptions have had a major impact on climate.

A "reversed" relation between volcanic eruptions and climate has been discussed by Rampino *et al.* (1979). He noticed that major eruptions like the Tambora in 1815 occurred during a period of general cooling. A possibility could be, he argued, that changes in climate caused increased stress on the earth crust and therefore increased the tendency for volcanic eruptions. The argument would explain the large frequency of major eruptions during Early Holocene, a time of major rearrangements of the load on the earth crust.

3.3.3 The greenhouse effect

The atmospheric content of greenhouse gases is important for the global radiance balance. The most important greenhouse gas is water vapour (Broecker, 1997; Valero *et al.*, 1997). A number of other greenhouse gases, which concentration in the atmosphere is natural or effected by human activity, such as CO_2, NH_4, N_2O, and O_3, have also an influence.

The effect on the radiation balance of water vapour varies with time and is also dependent on whether the vapour is forming clouds or not. The effect is therefore not expressed as a number, but it is of the order of 120 Wm^{-2}. Broecker (1997) has calculated that a decrease of the atmospheric water vapour content of 20% could lead to a temperature decrease of 3.5 +/-1.5 °C (2.4.2).

The atmospheric content of CO_2 has increased from 280 to 350 p.p.m.v. since the mid 1700s, when the industrial development started. CO_2 is efficient as a greenhouse gas when the concentration is low but it diminish exponentially with increasing concentration (Manabe and Bryan, 1985). At a concentration of around 350 p.p.m.v. the effect is about 3 Wm^{-2}.

CO_2 is likely to have influenced climate as a feedback forcing factor during glacial time because the concentration at that time was low (Brocker and Denton, 1990; Vostok project members, 1995). Relatively little is known about variations in the atmospheric concentration of CO_2 during the Holocene. Variations up to 5000 BP is given for the Byrd ice core, Antarctica (Neftel *et al.*, 1988) and variations during the Holocene has been calculated on basis of the isotopic composition of peat from southern South America (White *et al.*, 1994), which show variations between 215 and 315 p.p.m.v.. The two records are similar for the overlapping sector but the variations in CO_2 show no similarity with observed changes in climate.

The concentration of CO_2 in the atmosphere has increased by about 25% since the 1700s and most of this increase has taken place after 1950. The increase in CO_2 is frequently shown together with the global surface temperature for the last 100 years and a correlation seems obvious, particularly since it is pointed out that the temperature change during this 100 year period is unique. However, paleoclimatic records show that the temperature increase is not unique and modelling of climate using solar variability as the forcing factor reveals a close correlation where even the changes in the temperature trend around 1910, 1940 and 1975 is found, something a forcing by CO_2 do not reveal. It therefore seems like the effect of the 25% increase of CO_2 has had a minor influence on climate, something which also is accepted by IPCC in the 1995 version where it is claimed that “the balance of evidence suggests a discernible human influence on global climate” (Houghton *et al.*, 1996). The atmospheric concentration of CO_2 is likely to continue to increase within the near future. The effect of a doubling of the antropogenic increase of CO_2 and other greenhouse gases was in IPCC 1990 calculated to cause an increase in the radiation balance of 4 Wm^{-2} and to result in a temperature increase of between 1.9 and 5.2°C (Houghton *et al.*, 1990).

If the by IPCC predicted temperature increase will take place, this is likely to have an effect on global conditions. A model of the Greenland Ice Sheet respond to an increase to 710 p.p.m.v. and maintaining of this level shows that the ice sheet will melt away within about 3000 years (Loutre, 1995).

4 Discussion

Knowledge about past climate on all time-scales has improved considerably during last decades. By using sophisticated sampling techniques of sediments and precipitates from various sources, long continuous palaeoclimatic records have been constructed. Methods of analysis now permit close-interval sampling and yield data of high chronological resolution. Several new concepts, now being discussed, are likely to become general knowledge in a few years and some opinions may turn out to be wrong.

The presently accepted time-scale of the glaciations builds on a limited number of absolute age determinations of deep-sea sediments and tuning of the record to fit the Milankovitch theory. Many long records, e.g. pollen records, lake sediment records etc., lack independent age control. In these cases, similarities between the climate signal in the poorly dated records and the climate signal in other well-dated records are often used to construct a time-scale. This lack of independence strongly hampers the possibilities to test underlying mechanisms of the climate system and to understand patterns, forcing and feedback effects.

The ^{14}C dating technique can only be used for half of the last glaciation cycle and the dating technique in itself is problematic due to the fact that variations in the atmospheric ^{14}C content is only well known for the last 20 ka (Bard *et al.*, 1990). Other techniques for dating deep-sea sediments e.g. magnetic stratigraphy, marker horizons etc., have been applied, but the time-scale must still be regarded as approximate. Dating of deep-sea sediments is still largely dependent on the assumption of linear rate of sedimentation.

The uranium-series disequilibrium method has become an important tool in the precise dating of Quaternary events (Ivanovich and Harmon, 1992). Uranium-series dating has advantages to ^{14}C-dating in the respect that it yields calendar years and spans over a longer time period (>350 000 years). The precision of the technique has advanced remarkably during the last decade and the applications are increasing. The best materials for dating are corals and speleothems. Further development of methods for dating of material that have been build up under open-system conditions may, in future, allow the reliable dating of lake, spring and soil carbonates, peat, and archaeological material such as bones and teeth.

Dating ice-cores through counting of annual layers is possible for the last about 40 ka; thereafter an ice-model must be applied for obtaining the time-scale. The models are based on assumptions and are therefore not precise. In discussions of leads and lags, information from the same ice core is often used. This limits the problem of the dating and permits conclusions. However, not even using samples from the same core excludes errors, because air mixing occurs in the upper snow layers of an inland ice sheet during up to 1000 years after sedimentation. This may cause post-depositional alteration of the material. These limitations have been discussed extensively by Jaworowski *et al.* (1992). An example of a problem is the reaction between carbonate dust and volcanic acid precipitation, which appears to affect the CO_2 concentration in ice from Greenland. In spite of these limitations, the information obtained from ice-cores must be considered to be of exceptional high quality.

Although some controversy exist and the physical mechanisms behind are poorly understood, it appears firmly evident that long-term climatic variations, as the Quaternary glacial-interglacial cycles, are determined by orbital forcing, including the three cycles of 100 ka, 41 ka and about 23 ka length. These long-term climatic variations are modified and emphasised by internal feed-back mechanisms, such as a changing global albedo and changes in the atmospheric concentration of water vapour, CO_2 and other gases. The climate is also affected by forcing from atmospheric concentration of volcanic dust and variations in the cloud cover. The climate is further affected by changes in the atmospheric and oceanic circulation, which may or may not be forced by external forcing.

Variations in the solar radiation is a possible climate forcing factor that has been focus for much controversy because of problems in understanding the mechanisms behind the forcing. However, the strong correlation observed between solar cycles and global temperature variations on a short-term time-scale and the correlation between variations in the atmospheric concentration of the, by cosmic radiation produced, isotopes ^{10}Be, ^{14}C, ^{36}Cl and climate changes on a long-term time-scale, suggest that solar radiation is a possible climate forcing factor that deserves more attention in future studies.

Recent discoveries include the observation that major changes in climate seem to occur at the same time on both hemispheres, although the astronomical theory implies a time-lag between latitudes. This probably reflects the influence of feed-back effects within the climate system. However, while the conclusions on global symmetry builds on a firm number of climate data records from several regions in the Northern Hemisphere, detailed information on regional climate variability from the Southern Hemisphere and low latitudes is still scarce. Whether the rapid climate changes during the last glaciation occurred synchronously or with a time lag between the hemispheres is an important focus of the debate today.

For a long time it has been believed that the tropics remained quite stable during the Quaternary ice-ages. New evidence indicates that temperatures at low latitudes were about 5°C lower, or more, than the present values. There is a need for more continuous, terrestrial, high-resolution climate records from semi-arid to tropical regions to document and understand spatial and temporal patterns in climate. An increased number of local high-resolution palaeoclimatic data will facilitate regional and global comparisons, with the prospect of advancing the understanding of climate forcing factors.

Other consequences of recent research have been the confirmation that the Holocene in the Northern Hemisphere has been less stable than previously believed and that rapid climate fluctuations seem to be a normal process occurring at times of climate changing conditions. The forcing factors behind these rapid fluctuations are not well understood but are believed to be a result of major re-organisations in the oceanic circulation. Realising that nature, on it's own, can cause rapid climate changes of this magnitude put some perspective on the antropogenic global warming debate, where it is believed that the release of greenhouse gases will result in a global warming of a few °C. To understand the forcing behind natural rapid climate changes appears as important as to understand the role of man in changing climate, if accurate predictions of future climate changes are to be made.

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Abbreviations and acronyms

cal yr	calendar year.
ka	thousand years.
p.p.b.v.	parts per billion volume.
p.p.m.v	parts per million volume.
BP	Before Present, i.e. before 1950.
CLIMAP	Climate, Long-range Investigation, Mapping and Prediction (CLIMAP Project Members, 1976).
GISP2	Greenland Ice Sheet Project 2. (Alley *et al.*, 1993; Meese *et al.*, 1994).
GRIP	Greenland Ice Core Project (GRIP Members, 1993).
IPCC	Intergovernmental Panel on Climate Change (Houghton *et al.*, 1990).
Ma	Million years.
PDB	Isotope ratios of carbonate samples are expressed relative to a carbonate standard called Pee-Dee Belemnite, PDB (Faure, 1986).
SMOW	Isotope ratios of water samples are expressed relative to a standard called Standard Mean Ocean Water, SMOW (Faure, 1986).
SPECMAP	Spectral Mapping Project (Imbrie *et al*,. 1984).
WMO	World Meteorological Organization.

List of SKB reports

Annual Reports

1977-78
TR 121
KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

1979
TR 79-28
The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
Summaries
Stockholm, March 1980

1980
TR 80-26
The KBS Annual Report 1980
KBS Technical Reports 80-01 – 80-25
Summaries
Stockholm, March 1981

1981
TR 81-17
The KBS Annual Report 1981
KBS Technical Reports 81-01 – 81-16
Summaries
Stockholm, April 1982

1982
TR 82-28
The KBS Annual Report 1982
KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

1983
TR 83-77
The KBS Annual Report 1983
KBS Technical Reports 83-01 – 83-76
Summaries
Stockholm, June 1984

1984
TR 85-01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
Stockholm, June 1985

1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01 – 85-19)
Stockholm, May 1986

1986
TR 86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

1988
TR 88-32
SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, May 1989

1989
TR 89-40
SKB Annual Report 1989
Including Summaries of Technical Reports Issued during 1989
Stockholm, May 1990

1990
TR 90-46
SKB Annual Report 1990
Including Summaries of Technical Reports Issued during 1990
Stockholm, May 1991

1991
TR 91-64
SKB Annual Report 1991
Including Summaries of Technical Reports Issued during 1991
Stockholm, April 1992

1992
TR 92-46
SKB Annual Report 1992
Including Summaries of Technical Reports Issued during 1992
Stockholm, May 1993

1993
TR 93-34
SKB Annual Report 1993
Including Summaries of Technical Reports Issued during 1993
Stockholm, May 1994

1994
TR 94-33
SKB Annual Report 1994
Including Summaries of Technical Reports Issued during 1994
Stockholm, May 1995

1995
TR 95-37
SKB Annual Report 1995
Including Summaries of Technical Reports Issued during 1995
Stockholm, May 1996

1996
TR 96-25
SKB Annual Report 1996
Including Summaries of Technical Reports Issued during 1996
Stockholm, May 1997

List of SKB Technical Reports 1998

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Eva Hakami, Stig-Olof Olofsson, Hossein Hakami, Jan Israelsson
Itasca Geomekanik AB, Stockholm, Sweden
April 1998

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Johan Andersson[1], Karl-Erik Almén[2], Lars O Ericsson[3], Anders Fredriksson[4], Fred Karlsson[3], Roy Stanfors[5], Anders Ström[3]
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J A T Smellie (ed.)
Conterra AB
September 1998

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August 1998

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June 1998

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Svensk Kärnbränslehantering AB
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Claes-Göran Andersson
Svensk Kärnbränslehantering AB
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September 1998

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Jan Trägårdh, Björn Lagerblad
Swedish Cement and Concrete Research Institute
July 1998

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Pauli Saksa, Jorma Nummela
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