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survey and synthesis for the next century

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Future climate in the Nordic region

Abstract

The greenhouse gases carbon dioxide, methane, chlorfluorcarbons and nitrous oxide are increasing due to man´s activities. On physical grounds it is generally believed that this will influence the climate of the earth. Observational evidence, mainly global mean temperatures, indicate that the earth becomes warmer at present. It is, however, not possible to rule out that natural factors have caused observed changes until now. Swedish data show small or no trends at present.

The suggested scenarios for Sweden are given in interval form to express the large uncertainty. For temperature and precipitation in the years around 2030 we suggest the following changes compared with the levels around 1990.

	Winter temp.	Summer temp.	Winter prec.	Summer prec.
Northern Sweden:	0.5 to 1.5	0.0 to 1.5	0 to 15 %	0 to 10 %
Southern Sweden	0.0 to 1.0	0.0 to 0.5	0 to 15 %	0 to 10 %

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Future climate in the Nordic region - survey and synthesis for the next century

Summary

The greenhouse gases carbon dioxide, methane, chlorfluorcarbons and nitrous oxide are increasing substantially and will due to man's activities most probably continue to increase during the 21:st century.

The resultant forcing on the radiation processes causes, primarily, surface temperatures to rise. However, the climate system with its manifold of components and both positive and negative feedback mechanisms cannot be predicted, in the climate sense, with certainty. As one example the role of the oceans is not only to delay temperature changes but also to put great hazard onto regional scenarios because of possible changes of the oceanic circulation.

A closer examination of homogenized series of temperature, precipitation and air pressure from Sweden shows:

i/ The temperature decline from the optimum in the 1930:s and 40:s has levelled off and there are some uncertain indications of a recovery.

ii/ Precipitation is on a high level compared with the first decades of this century but there are no dramatic trends or changes in annual series. More surprising is the shift towards wetter winter half years and, in southern Sweden, somewhat drier summers.

iii/ The pressure difference between southern and northern Sweden (the local zonality) has recovered by at least 10% from a lower level 1930 to 1970. The latest very warm winters have been coupled to high zonality.

Surface global temperature series are much less variable than the Swedish series and they show:

i/ A clear increase during the latest 15 to 20 years.

This increase can be an effect of the enhanced greenhouse warming but it is also possible that natural factors have dominated.

The suggested scenarios for Sweden are given in interval form to express the large uncertainty. For temperature and precipitation in the years around 2030 we suggest the following changes:

	Winter temp.	Summer temp.	Winter prec.	Summer prec.
Northern Sweden	0.5 to 1.5	0.0 to 0.5	0 to 15%	0 to 10%
Southern Sweden	0.0 to 1.0	0.0 to 0.5	0 to 15%	-5 to 10%

It is argued that northwestern Europe will be an area of less rapid warming than more continental regions on a possible general warming.

This document must be updated when new findings are available from the on-going international research.

Sammanfattning

Växthusgaserna koldioxid, metan, klorfluorkarboner och kväveoxid ökar i betydande grad och kommer sannolikt att fortsätta öka på grund av människans aktiviteter under nästa århundrade.

Påverkan på strålningsutbytet medför, primärt, en ökande temperatur vid markytan. Klimatsystemet, med sina oräkneliga komponenter och positiva och negativa återkopplingsmekanismer, kan emellertid inte förutspås, i dess klimatologiska mening, med säkerhet. Som ett exempel är oceanernas roll inte endast att fördröja temperaturförändringar utan de utgör också ett stort osäkerhetsmoment när det gäller regionala förändringar på grund av eventuella förändringar av havsströmmarna.

Betraktar vi homogena serier av temperatur, nederbörd och lufttryck från Sverige finner vi att:

i/ Temperaturnedgången från optimet på 30- och 40-talen har stannat av och det finns tecken, dock osäkra, på en viss uppgång.

ii/ Nederbörden ligger på en hög nivå jämfört med seklets början men några mer dramatiska förändringar syns inte i årsnederbörden. Mer överraskande är förskjutningen mot blötare vinterhalvår och, i södra Sverige, något torrare somrar.

iii/ Lufttrycksskillnaden mellan södra och norra Sverige har återhämtat sig med åtminstone 10% från en lägre nivå 1930-70. De senaste mycket milda vintrarna har varit ovanligt starkt zonala.

De globala temperaturserierna varierar mindre än de svenska och visar:

i/ en klar uppgång under de senaste 15 till 20 åren.

Denna ökning kan vara en effekt av en ökande växthuseffekt men det är också möjligt att naturliga faktorer har dominerat.

De föreslagna scenarierna för Sverige har givits i intervallform för att betona den betydande osäkerheten. För temperaturen och nederbörden runt år 2030 har följande förändringar föreslagits:

	Vinter temp.	Sommar temp.	Vinter nbd	Sommar nbd
Norra Sverige	0.5 till 1.5	0.0 till 0.5	0 till 15%	0 till 10%
Södra Sverige	0.0 till 1.0	0.0 till 0.5	0 till 15%	-5 till 10%

Vidare hävdas att nordvästra Europa är ett område som reagerar långsammare än mer kontinentala områden på en eventuell allmän temperaturhöjning.

Detta dokument behöver uppdateras i takt med att nya forskningsrön kommer fram.

1 Introduction

The earth's global mean surface temperature has during the last million years fluctuated by 4-5 degrees Celsius: ice ages and warmer interglacial periods have been interchanged on a timescale of about 100 000 years. The latest ice age ended about 11 000 years ago and the global average surface temperature has then to the present time fluctuated with 1-2 degrees.

The issue that occupies climate researchers all over the world today concerns the question whether we are approaching a dramatic climate change during the coming 100 years due to human activities. This climate change is estimated to about 2-5 degrees during the coming century. This would correspond to a change in the climate which the earth has not experienced since the last transition from ice age to the present interglacial age and which means that the global climate can reach a temperature level which has not been exceeded during the last 100 000 years.

The chemical composition of the atmosphere has been changed during the last century because of pollution from industries and other exhausts due to human activities. The interest is foremost focused upon the consequenses due to the increase of so called greenhouse gases, which are atmospheric constituents of the gas mixture and which is of fundamental importance for the earth's radiation budget.

In 1988 an international panel, IPCC (Intergovernmental Panel on Climate Change), was established to assess the scientific information related to the climate change issue and to formulate realistic response strategies. The outcome of the IPCC was presented in 1990 and presently this synthesis is updated and new results will be presented during 1992.

During the past century the population on the planet has increased to about five billion (5×10^9) inhabitants. The emissions from the industrialized world together with increased agricultural activites has caused large environmental problems.

Important issues are:

- Is the global climate affected significantly by human activities? If a climate change is underway: to what extent and how fast will the change occur?

- What are the environmental and socio-economic consequenses?

- What response strategies should be applied to reduce/eliminate the negative effects?

2 Climate change - principal mechanisms

<u>Astronomical factors - the timescale > 10 000 years</u>
Prominent in the Earth's history is the 100 000 year Pleistocene glacial-interglacial cycles when climate has mostly been cooler than at present (Imbrie and Imbrie, 1979). This period began about 2 million years ago and was preceded by a warmer epoch with limited glaciation. Global surface temperatures have varied by about 4-5 degrees through the Pleistocene ice age cycles. Large changes of ice volumes and sea level have occured. Within the equatorial belt the temperature changes have been quite small or 1-2 degrees but in higher latitudes like Scandinavia up to 10 degrees.

These recurring glaciations are believed to be a consequence of variations in seasonal radiation receipts in the Northern Hemisphere connected with small changes in the distance of the earth from the sun. One of these so-called Milankovitch orbital effects are connected with the fact that the earth's orbit around the sun changes from a relatively circular shape to a more elliptical shape in the course of time. Such a cycle takes about 110 000 years and gives a change in the incoming direct solar radiation of 0.014 to -0.17 percent of the present flow of solar radiation.

Differences in radiation receipt from the sun between summer and winter are connected with the tilt of the earth's axis which is changing with a period of 41 000 years. Another astronomical factor is connected with the position of perihelion, which concerns the point in the earth's orbit which is located closest to the sun. This point is affected by the gravitation influence from other planets such as Jupiter and cause two periodicities, 23 000 and 18 800 years. Presently perihelion occurs in January, but in about 11 000 to 15 000 years it will occur in July.

Periodicities in the climate with roughly the same frequency as the above astronomical mechanisms have been traced at analysis of bottom sediments in the Indian ocean (Imbrie and Imbrie, 1979).

The changes in solar radiation due to the astronomical factors are rather small. To create a significant climate change the changes due to the astronomical factors have to be amplified in some way. It is generally believed that feedback mechanisms inherent in the climate system can act in this amplifying way - see feedback mechanisms below.

<u>The greenhouse effect</u>
All bodies are emitting radiation and the warmer a body is the more intense - and shifted towards shorter wave lenghts - is the emitted radiation. The earth's radiation climate is determined by the incoming solar radiation, which is of the short-wave type due to the sun's high temperature, the albedo of the earth-atmosphere and the long-wave radiation characteristics of the atmosphere and the earth's surface.

About one third of the solar radiation is reflected back to space due to clouds, snow, ice and other reflecting surfaces (albedo). The remaining two thirds of the solar radiation is absorbed by the atmosphere, the oceans and the land surfaces.

If there was no atmosphere around the globe a temperature at the earth's surface of about -18 degrees would be enough to give the outgoing long-wave radiation that could balance the incoming solar radiation. This means a frozen world with limited possibilities for life.

The fact that we have an atmosphere means that the balance between the incoming and outgoing radiation is maintained in the following way. Short-wave radiation can pass through the clear atmosphere relatively unimpeded. But long-wave terrestrial radiation emitted by the earth is to a large extent absorbed by the atmosphere by the so-called greenhouse gases, water vapour, carbon dioxide (CO_2), methane (CH_4) and some further gases. These gases then re-emit the radiation in all directions including the direction towards the earth's surface. Since, on an average, the outgoing long-wave radiation balances the incoming solar radiation, both the atmosphere and the surface will be warmer than they would be without the greenhouse gases. The radiation characteristics of the atmosphere are to a great extent controlling the heat budget and the temperature of our planet.

This so-called greenhouse effect means that the earth's average surface temperature is about 15 degrees, or around 33 degrees warmer than it would have been in the case of no atmosphere surrounding the earth. Venus has a greenhouse warming of about 520 degrees and Mars 10 degrees.

The main greenhouse gases in the atmosphere are water vapour (dominating), carbon dioxide, methane, nitrous oxide, chlorofluorocarbons (CFCs) and ozone. Water vapour has the largest greenhouse effect, but its concentration is determined internally within the climate system. If the planet will warm than the concentration of water vapour will increase and thus enhance the greenhouse effect. Carbon dioxide, methane, nitrous oxide and CFCs have increased dramatically during the last century due to man's activities.

The concentration of ozone is decreasing in the stratosphere and increasing in the lower part of the troposphere due to human activities and the quantitative greenhouse effect is consequently difficult to quantify for this gas.

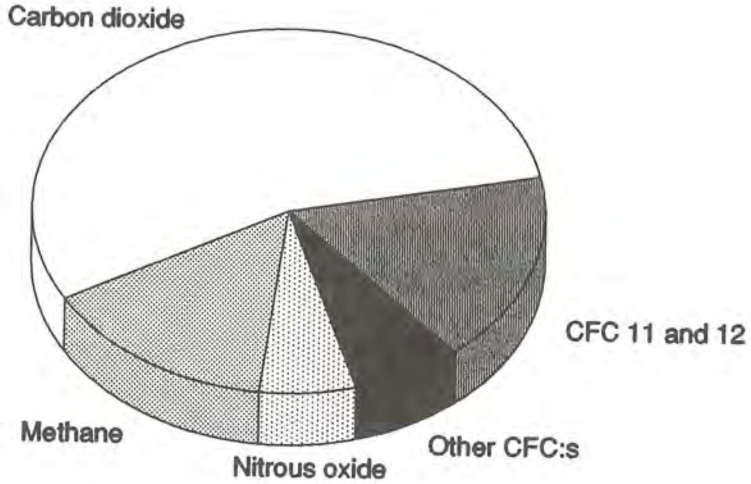


Figure 1: The contribution from each of the human-made greenhouse gases to the change in radiative forcing from 1980 to 1990.

Figure 2 illustrates the variation of temperature and carbon dioxide during the last 160 000 years in Vostok, Antarctica. By analysis of ice cores that have been taken from a more than 2 km deep hole in the ice it has been possible to quantify these two parameters during the course of time (Barnola et al, 1987). These data covers the last glacial and interglacial periods and even covers part of the ice age which was ended about 160 000 years ago. It is quite obvious from this series that the greenhouse effect can act as an important positive feedback mechanism. An important aspect of this is that a warmer ocean has less capacity to dissolve carbon dioxide than a colder one.

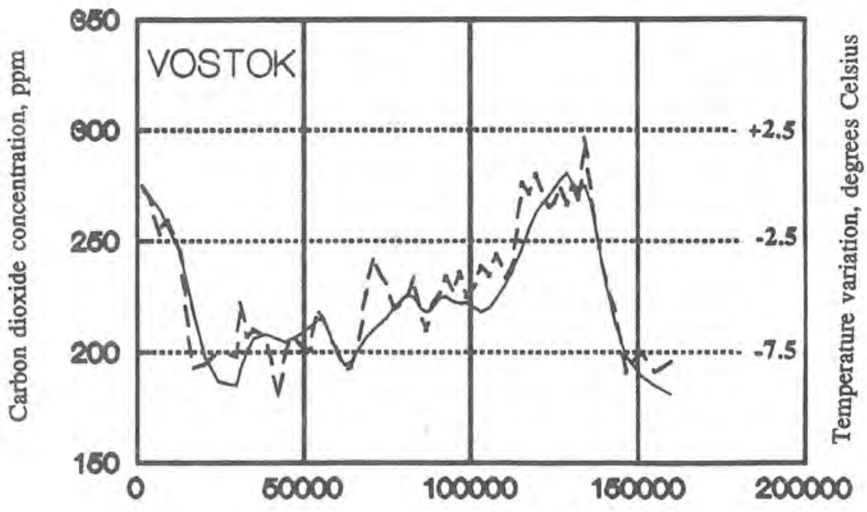
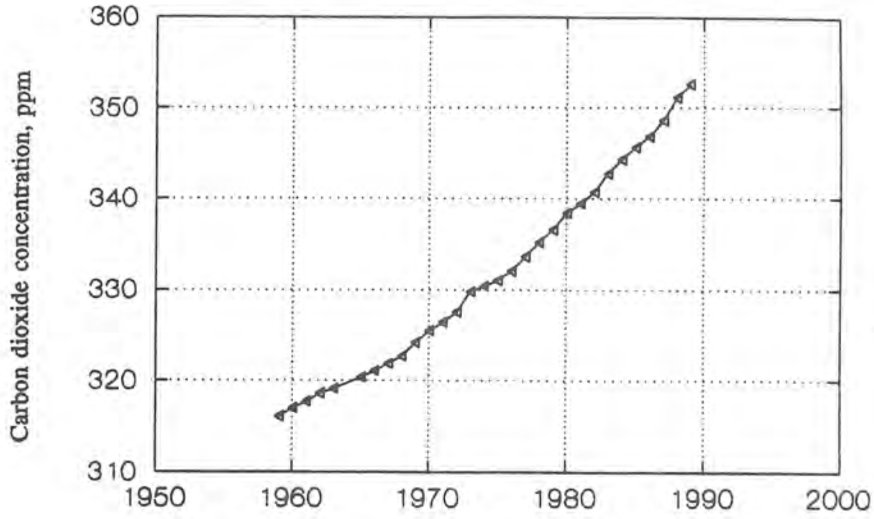


Figure 2: Inferred temperature deviations (oxygen isotope method) (dashed line) and concentrations of carbon dioxide (solid line), 160 000 up till now.

Direct measurements of the atmospheric content of carbon dioxide have been undertaken since 1958. The observation data from the Mauna Loa Observatory on Hawaii are illustrated by the diagramme below.



<u>Figure 3:</u> The atmospheric concentration of carbon dioxide 1958-1989, Mauna Loa, Hawaii.

From the figure illustrating the carbon dioxide content at Vostok and at Mauna Loa it is clear that the present level, 355 ppmv (part per million by volume), has not occured during the last 160 000 years. In fact, before the industrialization the concentration never reached above 300 ppmv during Pleistocene.

The life cycle for coal is not fully understood (B Bolin, 1986) concerning the role and effect of natural sources and sinks. One main task is to understand to what extent the oceans can absorb carbon dioxide now and in the future. It is estimated that about half of the release during this century has been absorbed by the oceans. Further chemical and biological reactions in the oceans are also important for the coal budget.

As indicated by Figure 1 carbon dioxide is dominating the human affected greenhouse gases, but it is clear that the greenhouse effects of methane, nitrous oxide, chlorofluorocarbons also are important. The concentration of all these gases have increased during the last decades.

In the scenarios presented in Section 5 we will tacitly assume that the future emissions of greenhouse gases will be that of scenario A in the IPCC-report. However, the interval form used is also intended to cope with not too drastic deviations from the scenario A curve.

<u>Influence on the climate from aerosols</u>

Particles or aerosols in the atmosphere can affect the climate through absorption or reflection of solar radiation. Stratospheric aerosols arise mainly from volcanic eruptions and can result in increased reflection of solar radiation back to space and consequently in a cooling of the climate. The life time for dust particles in the stratosphere is usually about one year but after extreme eruptions the reduction of sunshine can be measured for two to three years. Thus the climate effect due to volcanic eruptions is limited in time.

Typically a heavy eruption gives a reduction of the solar radiation of one or a few percent on a regional or hemispheric scale. But in rare cases the reduction can be much larger as over Europe from July to September 1912 when at least 20% of the normal direct radiation did not reach the ground (Kyncl et al, 1990). This was the result of the enormous eruption of Katmai, Alaska 6-7 June 1912 when 20-28 km^3 of material was thrown into the atmosphere, twice as much as the Krakatoa explosion produced in 1883.

Examples of eruptions which have probably affected the global climate during one or some years are Tambora in 1815 (with the year 1816 mentioned as the year without a summer), Krakatoa in 1883, Katmai in 1912, Agung in 1963, El Chichón in 1982 and Pinatubo in 1991. It has recently been suggested in an updated IPCC-section that the Pinatubo eruption (together with Cerro Hudson in southern Chile) will reduce global mean temperatures by 0.3-0.5 degrees, or possibly more, over the next 2-4 years.

Industrialization, impurities from cities, modern agricultural methods and the pressure from population in semiaride regions have increased the concentration of dust in the lower part of the atmosphere. Due to the fact that dust can act as condensation particles the cloudiness and the optical properties of clouds can be affected and hence change the radiation budget.

The residence time in the troposphere of these impurities are much lower than the particles in the stratosphere since they are washed out by precipitation and/or subjected to dry deposition.

In certain conditions, for instance absorbing haze in the Arctic region, anthropogenic aerosols can have a warming effect. The dominating radiative impact of these aerosols is definitely one of cooling.

Of special concern is the atmospheric content of sulphate particles in cloud free parts of the atmosphere. These particles can reflect part of the solar radiation back to space. The particles can also act as cloud condensation nuclei. If the number of cloud droplets in the clouds are increased the albedo effect (reflection) can increase.

The net result of the increased sulphate particle content is probably a cooling of the atmosphere. This effect is largest in the industrialized part of the world and consequently much more significant on the northern than on the southern hemisphere.

There are estimates (Charlson et al, 1991) which indicate that this effect averaged over the northern hemisphere is about -1.1 Wm^{-2}, which is comparable but opposite in sign to the present-day radiative forcing by antropogenic carbon dioxide, +1.5 $Wm^{-2.}$

The sun

Recently some tentative suggestions on the coupling between sunspot activity (Reid, 1991) and sunspot cycles (Friis-Christensen and Lassen) on the one side and the solar irradiance on the other have been put forward. The agreement between the latter sunspot indices and temperature data sets is strikingly good. As there are no clear physical or statistical connections to the solar irradiance the interpretation of these results is still not yet clear. Also there are some quite arbitrary choices of weighting factors involved in the processing of sunspot data.

Direct measurements of the solar irradiance (the solar constant, about 1350 - 1380 W/m^2 on a surface at right angle with the solar beams at the top of the atmosphere) does not show any significant changes yet. Satellite based sensors have increased the accuracy of these measurements, but have only been in operation for quite few years.

Feedback mechanisms

The water vapour - a positive feedback

A warmer atmosphere can hold more water vapour - the most important of all greenhouse gases. If we calculate the direct effects of a CO_2 doubling to 1.2°C the positive feedback of water vapour (clouds not taken into account) have been estimated to about 1.7°C (Mitchell, 1991).

The albedo effects of snow - another positive feedback

The high albedo of snow acts to enhance the drop in temperature and vice versa for a naked soil. It is thought to be a less important positive feedback mechanism than the water vapour effect for the globe as a whole but is very crucial for the boreal zone where it is responsible for the extra large temperature increases during winter and spring in model simulations of a CO_2 doubling.

The clouds - an uncertain coupling

Although on the average clouds cool the atmosphere (water phase transformation and evaporative properties neglected) different cloud types on different altitudes and latitudes give different contributions to the radiation budget. One realistic effect of an initial warming would be an increase of water clouds and decrease of ice clouds. As water clouds have longer residence times in the atmosphere a compensating cooling could offset some part of the expected warming (Rowntree, 1990; Mitchell et al, 1989). But other studies indicate that it is too early to say if the net effect of cloud changes acts as a positive or negative feedback mechanism (Ingram, 1989).

The oceans

In the upper 2.5 metres of the sea there is about the same amount of heat as in the whole atmosphere. This large heat capacity can delay a future warming of the atmosphere considerably, at least some decades. An increased greenhouse effect can, however, not disappear in the sea: heated oceans will give a thermal expansion which will be evident from a rise of the sea level! Also heated oceans will subsequently warm the atmosphere.

The huge water masses of the oceans slow down and delay any temperature change occurring primarily in the atmosphere. The slowing down depends on the vertical mixing rates in the oceans and on the exchange of heat at the surface.

Equilibrium simulations uses fixed CO_2 levels (say doubled) during the whole experiment run while transient simulations uses a more realistic technique with successive increase in concentration, see further section 4.

Simulations with transient, coupled atmosphere-ocean models indicate that so called equilibrium simulations give - roughly - a factor two larger increases in temperature than transient models within the next century (Cubasch et al, 1991). This is then mainly a consequence of the slowing down mechanism.

The effect on and from ocean currents are as yet a quite large uncertainty factor in climate modelling, especially for regional interpretations. The Gulf stream touching Scandinavia can be sensitive to minor circulation changes and to the extent of ice in the Arctic region. The Gulf stream is important to ameliorate winters in the maritime regions. Especially when cold air flows out from Russia to the North sea and the Norwegian sea the heat reservoar of these warm waters is very effective in breaking up the cold inversion.

We should also mention the importance of the salinity of the surface water. It has been suggested that the salinity of the water in the north Atlantic area is important for the sinking of water and the formation of deep water. Rather modest changes of the salinity can give rise to large displacements of sinking zones and the surface currents (Covey, 1990) with substantial implications for the climate of northwest Europe.

Inherent fluctuations in the climate system

It is believed that ocean temperature fluctuations and ocean currents play an important role in creating global scale and regional changes on the time scale from years to decades. One striking example is the El Nino or El Nino/Southern Oscillation (ENSO) fluctuation in the Pacific which also exerts some influence on parts of the extratropical regions. ENSOs occur every 2-8 years, with each event lasting for 1 - 2 years.

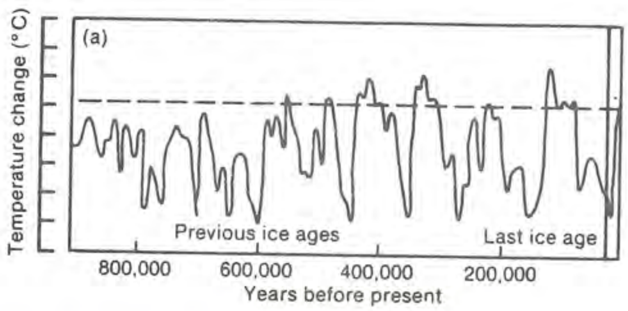
In the extratropical regions inherent variations can be initiated by one or a few dramatic synoptic scale events like a strong outflow of cold air that becomes the starting point of a major change in the large scale weather pattern and with consequenses for extent of snow cover and cyclone developments.

The physical understanding of so called natural fluctuations is limited. As one example we can mention the behaviour and control of ocean currents. But more principal studies of the interannual variability in the light of the behaviour of simplified dynamic systems of the atmosphere have shown that substantial inherent variations can develop (Lorenz, 1990, Trenberth, 1990).

3 Historical fluctuations in the climate

<u>Climate fluctuations during the past 2 million years</u>

The 100 000 year glacial-interglacial cycles began about 2 million years before the present time. Global averaged surface temperatures have typically varied by 4-5 °C through this period's (the Pleistocene) ice age cycles. In some middle and high latitudes of the Northern Hemisphere the temperature variations have been as great as 10 - 15°C. Figure 4 illustrates the temperature pattern during this period. The global sea level was about 120 m below the present level during the glacial periods and ice sheets of continental size covered much of North America and Scandinavia. As indicated in section 2 it is believed that astronomical factors are the principal mechanism for these climate fluctuations.



<u>Figure 4:</u> Schematic figure of the temperature variations during the latest one million years.

The last ice age ended about 11 000 years ago. A short period of abrupt reversal of the general warming trend occurred around 10 500 before the present time (BP). The factors causing this significant fluctuation are not definitely identified. Due to the fact that the signal was strongest in the North Atlantic region it has been proposed that this fluctuation might have been caused by changes of the sea surface temperatures of the North Atlantic Ocean. The melting of the large ice sheet volumes resulted in a large influx of low density freshwater into the North Atlantic ocean, which probably reduced the rate of deep water production. Hence, the oceanic circulation might have been affected and in particular the currents of the North Atlantic. The general flow pattern of the North Atlantic, with the northward transport of waters in the surface layers by the Gulf Stream, a sinking in the area of Spitzbergen and a return flow at depth, might then have been disturbed.

This episode which occurred in the Younger Dryas period is of particular interest due to the fact that a warming due to increased amounts of greenhouse gases might give a similiar outcome. The basic difference is that during the Younger Dryas period the relatively light water was due to fresh water and during a global warming event it would be caused due to warming of the sea surface by a warmer atmosphere.

The period - Holocene - after the deglaciation contains a climatic 'optimum' about 5000 - 6000 years ago with a warmer climate, particularly during summer.

During the last 1000 years particular interest has been focussed on the so-called Little Ice Age, which occured in many regions during the period 150 to 450 years ago. During this period most continental glaciers were advancing. Studies of tree-ring data have given more details concerning the 'Little Ice Age'. Probably it was not a general global cooling of the planet but rather a chain of episodes with warm periods in between. Figure 5 gives an illustration of the flucutuations contained in tree-ring data from Torneträsk in northermost Sweden. The tree-ring width in northern Scandinavia is fairly well correlated with summer temperatures (during the growing season). Correlation coefficients are usually about 0.5 to 0.6.

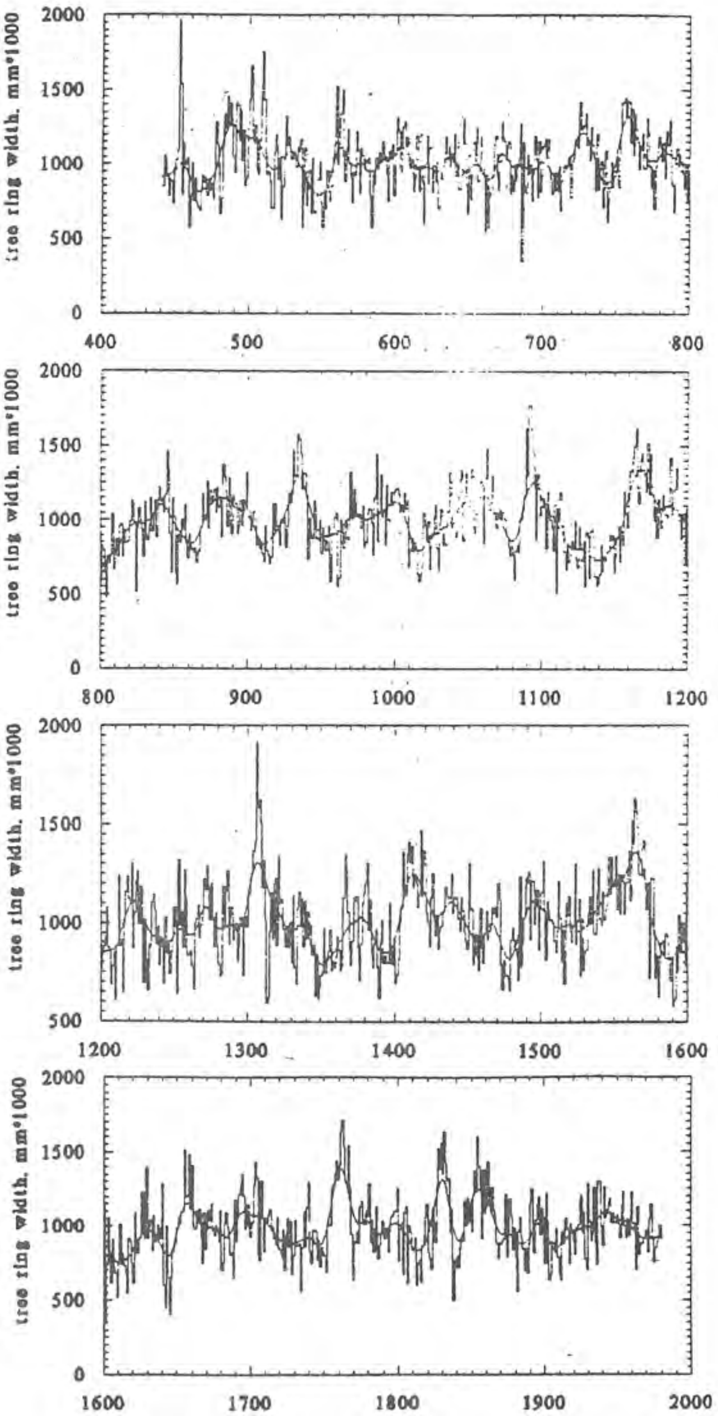


Figure 5: Tree ring width from 450 until today, Torneträsk, northwestern Sweden.

Much interest has been focussed on the Little Ice Age due to the fact that there are ideas that the global warming of the last century might be a result of a 'recovery' of the climate as a result of the Little Ice Age rather than due to greenhouse gases.

Atmospheric surface temperature since the middle of the 19th century

Based on meteorological observations since 1856 hemsipheric and global temperatures have been estimated as illustrated by Figure 6 (Parker and Jones, 1991). The data are based on observations from land stations and observations at sea from ships. From this information it is concluded that the earth has been subjected to a warming during the last century. If the average temperature for 1981-1990 is subtracted from the average temperature during the last two decades of the previous century the result is 0.43 degrees for the globe. For the northern hemisphere the corresponding difference is 0.45 degrees and for the southern 0.42 degrees.

The increase between 1900 and 1940 of about 0.3 degrees occured before the main increase of greenhouse gases and could possibly be considered as an example of a typical natural, inherent change. The strikingly warm years in the latest two decades could be a response to the increase of greenhouse gases. To illustrate this difficult task of interpretation we cite some lines from Parker and Jones (1991):

"On physical grounds, and in the light of an increasing volume of numerical modelling studies, it is becoming increasingly probable that the enhancement of the greenhouse effect, through the input of carbon dioxide and other gases into the atmosphere, is contributing to the recent warming. However, this cannot yet be proved (Wigley and Barnett, 1990), because strong warmings have happened in the past without major changes to greenhouse gas concentrations, e.g. the large warming 1920-1940. Thus the most recent warming is likely to include contributions from natural causes."

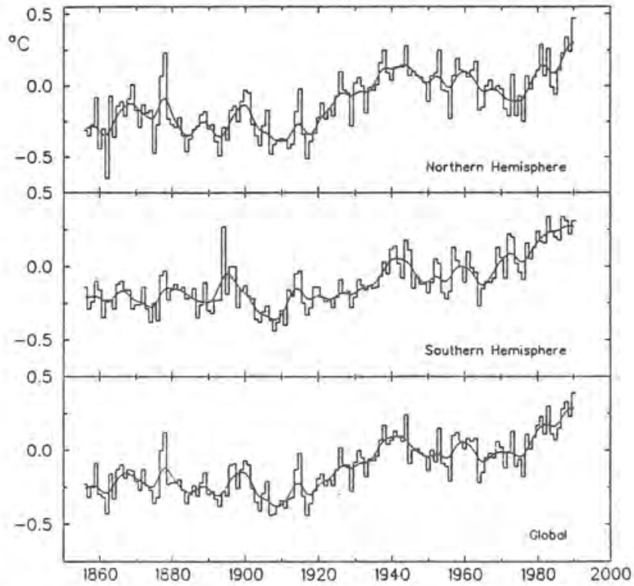


Figure 6: Hemispheric and global surface temperature anomalies (with respect to 1951-80) for 1856-1990 (Parker and Jones, 1991).

There are several uncertainties in this stock of data:
- the spatial coverage is deficient and varies very much, particularly during the first decades of the time series
- the instructions and routines which the observers have used have been changed during the course of time
- the exposure of the thermometers have been changed
- changes have occured in the surroundings of the stations and not least urbanisation

Several studies have been concentrating on the quality of the observations and on the estimate of the magnitude of the various error sources inherent in the observations.

Particular interest have been focussed on the fact that many stations have changed their environment due to urbanisation. Within urban areas it is a well-known fact that often a heat island will be generated with higher temperatures than in the corresponding rural areas. This heating effect is a reality, but of a too local representativity to be used for estimating the temperature over a larger region where the major area is of a rural type. Several studies of this effect have been undertaken (see for instance Jones et al 1986, Karl et al, 1988). An opposite effect has arisen during some decades after 1940 when many meteorological stations moved from cities to, in most cases, colder situated airports in the rural areas. The urban effect have been estimated to be around 0.1 degree in 100 years in the global averages, but further studies are going on to clarify the size of this error source.

The temperature in the troposphere and the stratosphere during the latest decades

Global climate models predict that a heating due to the greenhouse effect will affect large parts of the troposphere and that the stratosphere cools. The troposphere extends from the earth's surface up to between 8 km (polar latitudes) and 18 km (equatorial region).

It is of interest to verify these predictions by observations. Global temperature values for layers in the troposphere and the stratosphere (above the troposphere) have been derived by use of radiosonde data (Angell, 1988). There are several uncertainties connected with these estimates, the representativity in space and the quality of these data. 63 radiosonde stations have been used. The majority (60 %) of the stations are situated on the northern hemisphere, but they have nevertheless a relatively good distribution in space.

The results indicate a cooling in the stratosphere while the trend in the middle of the troposphere is uncertain.

The nordic climate since the middle of the 19:th century

Considering homogenized series from two regions in Sweden we can recognize some of the features of the global temperature series, mainly the rather rapid warming during the first third of this century. Especially data from northern Sweden indicate that the optimum in the 1930:s and 40:s is followed by a decline up to about 1970.

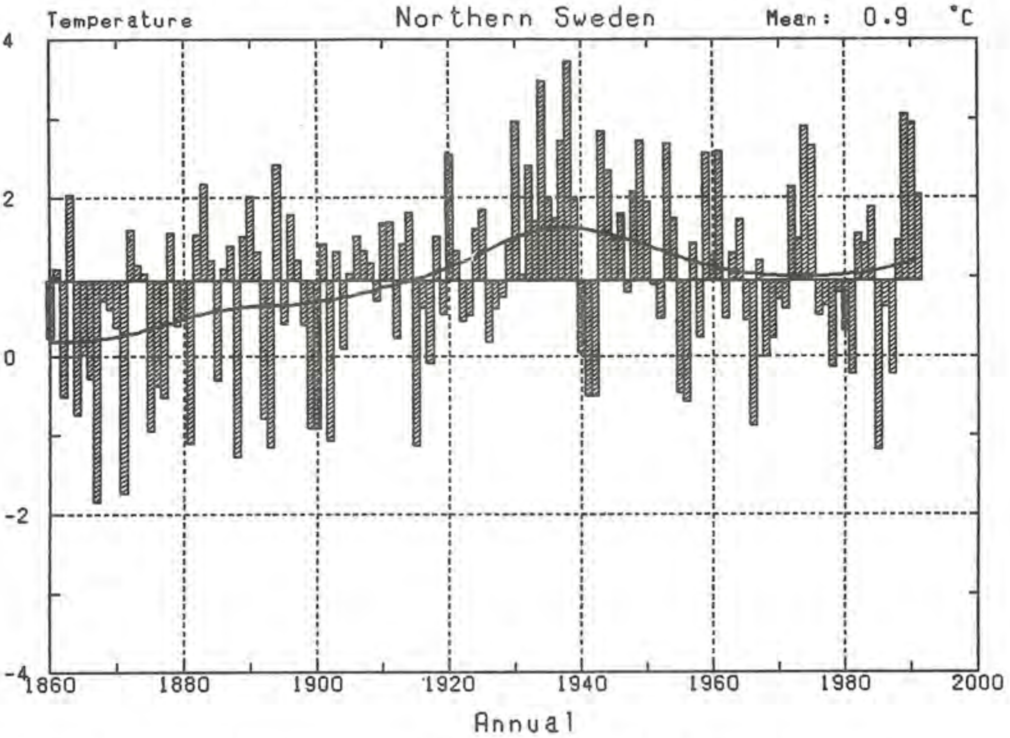


Figure 7. Annual temperatures 1860-1991 based on five stations in northeastern Sweden (the northern region). The smoothed curve is obtained by a Gaussian low pass filter with a standard deviation of 9 years.

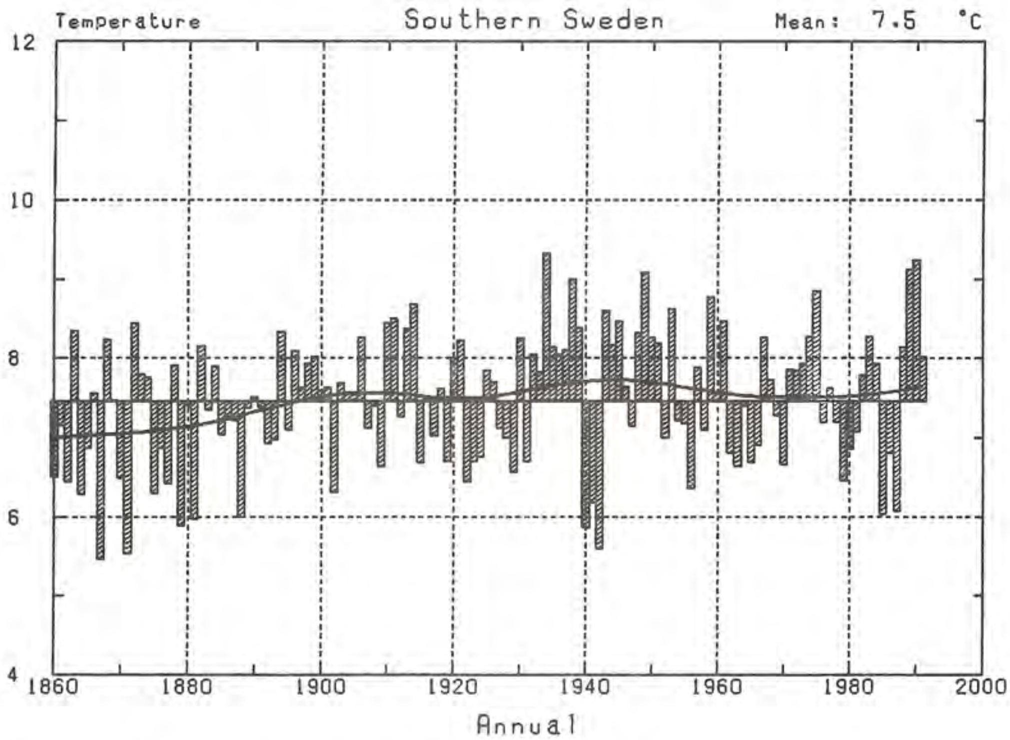


Figure 8. Annual temperatures 1860-1991 based on five stations in southeastern Sweden (the southern region).

During the latest two to three decades there has been a mixture of both very cold and very warm winters giving an unclear picture of present trends in Sweden, see Figure 9. The large interannual variability is typical for our region and is most marked in the north and in winter. Warm winters are typically connected with strong zonal, westerly or southwesterly airflow when much heat is imported and clouds and winds prevent strong inversions to build up. Cold winters are characterized by anticyclonic weather with weaker winds and drier subsiding air.

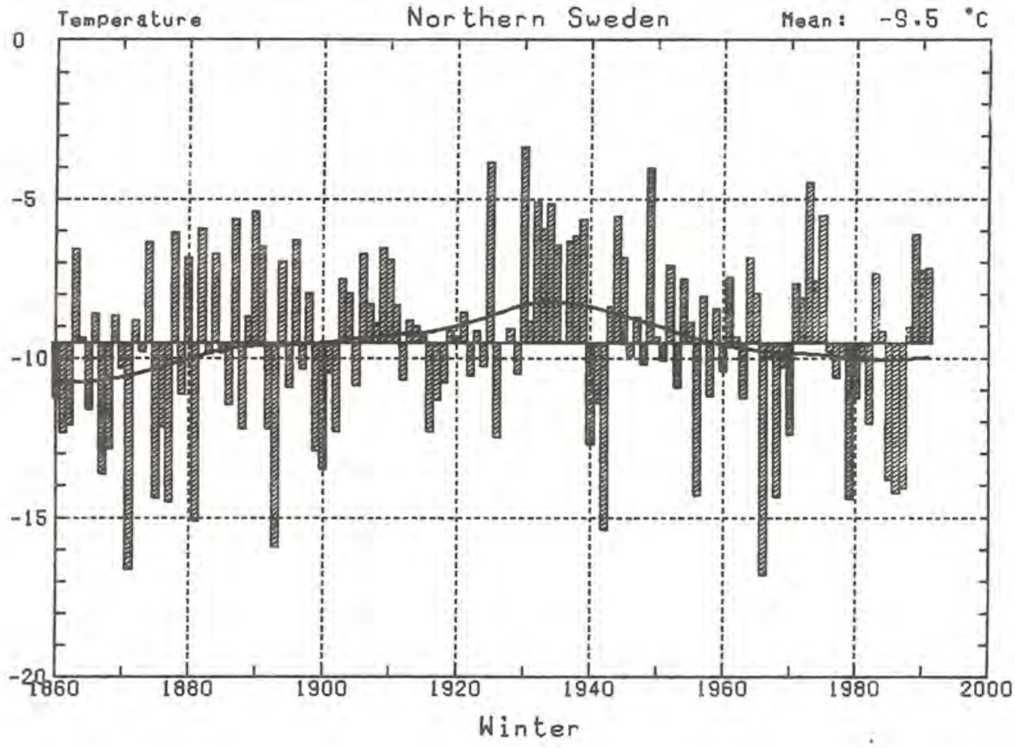


Figure 9. Winter (Dec-Feb) temperatures 1860-1991 in the northern region. December is from the previous year.

Mild winter episodes in Scandinavia are often connected with bitterly cold air and northerly winds over Labrador and western Greenland. These compensating effects within the extratropical zones explain the much larger interannual variability in regional data than in global averages. This makes it more difficult to use regional series in climate change studies. On the other hand regional changes are often of greater concern in impact studies and for individuals.

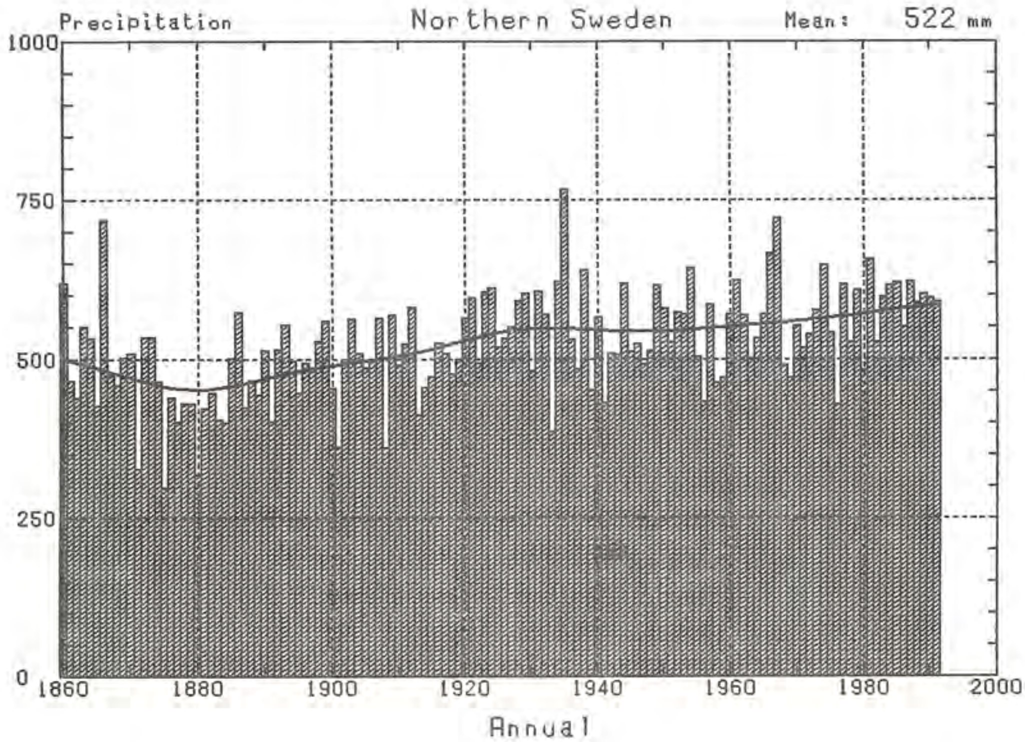


Figure 10. Annual precipitation sums 1860-1991 in the northern region.

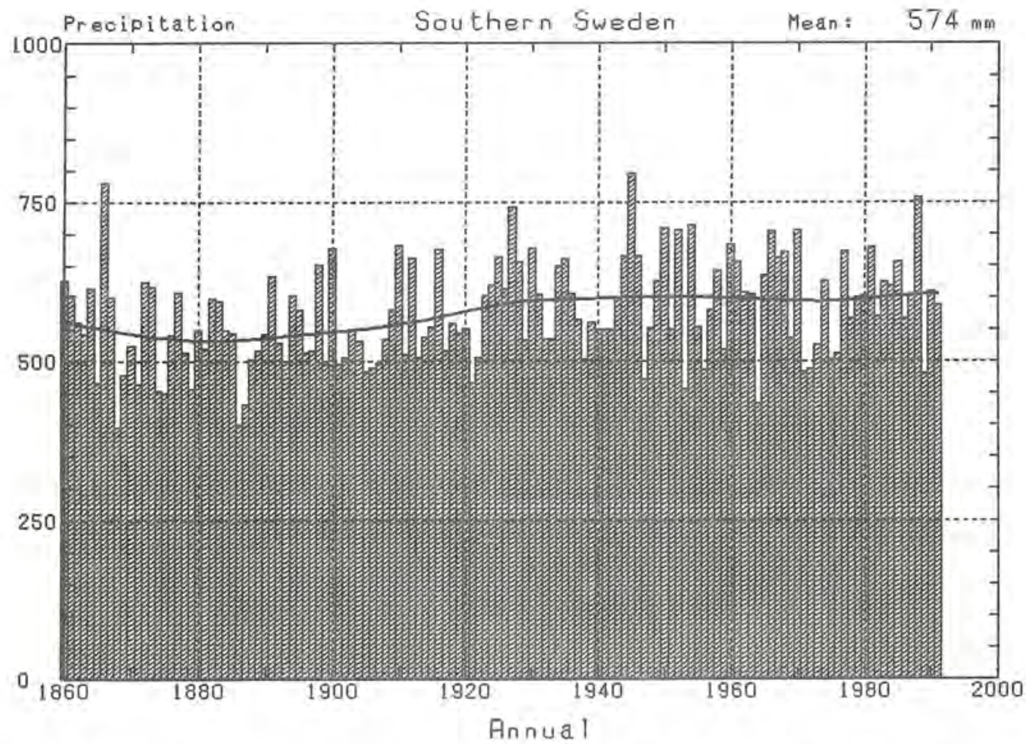


Figure 11. Annual precipitation sums 1860-1991 in the southern region.

The drier period in the late nineteenth century could be interpreted as a consequence of many cold and anticyclonic episodes during the winter half year. Thus there is some degree of consistency between temperature and precipitation data. But to some extent the drier earlier years can also be due to less good sheltering of the guages and less reliable instruments - in spite of our efforts to correct or omit less good series.

Further studies are needed for revealing the underlying regional climate relationships.

During the latest 50 years there is some indication of an increase of precipitation in the northern region while the smoothed curve is almost a horizontal line in the south. Separation with regard to season indicates wetter winter half years in almost the whole of Sweden and somewhat drier summers in the south. This tendency is most marked in the wet districts in the southwest like in Havraryd in Halland. Wetter winter half years and drier summers in the south could indicate a small poleward shift of the cyclone tracks and it will be of great interest to see if this tendency will hold or even be stronger in the near future. An even more striking shift in the same direction has been presented recently using the England-Wales series (Marsh and Monkhouse, 1991).

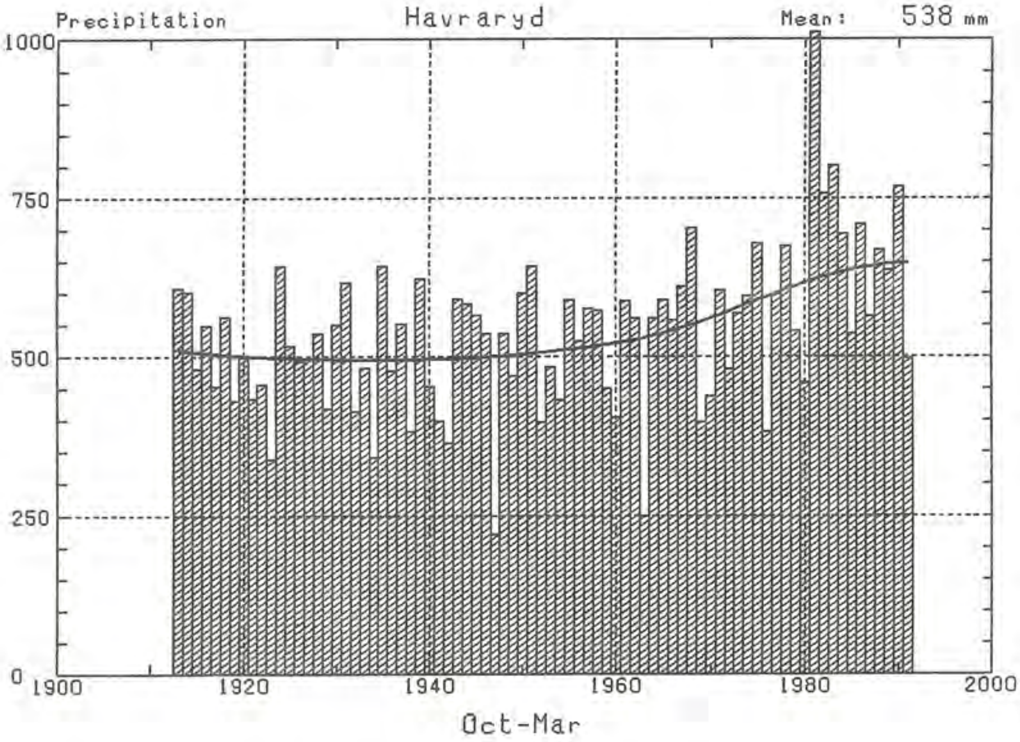


Figure 12. Winter half year (Oct-Dec previous year, Jan-Mar actual year) precipitation sums 1913-1991 in Havraryd, southwestern Sweden.

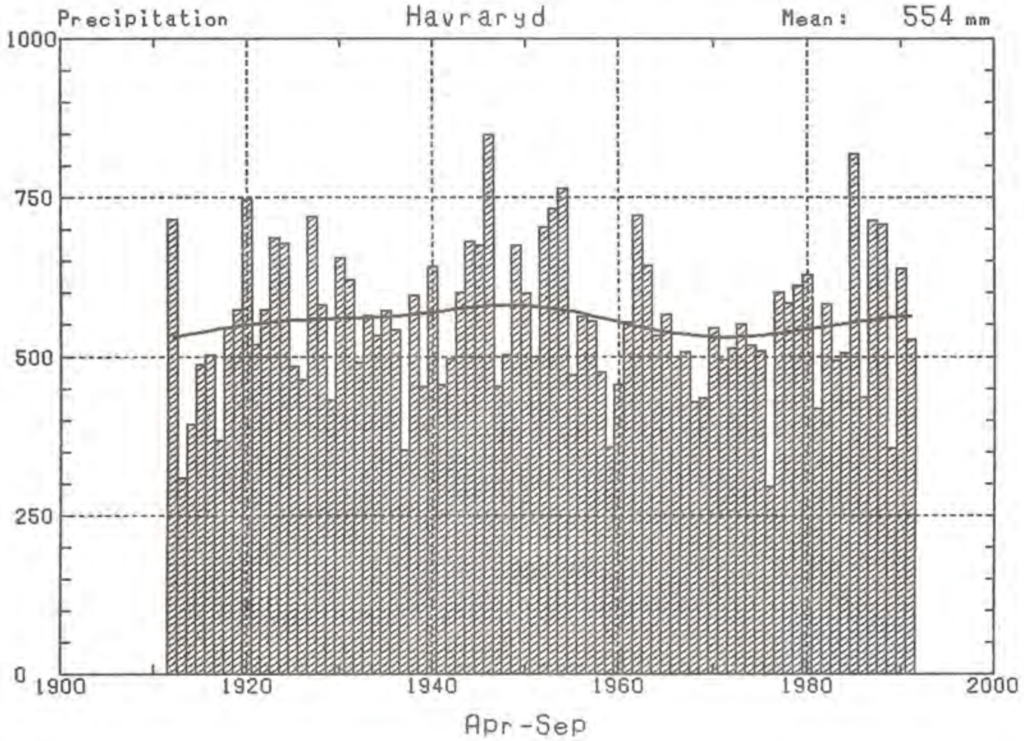


Figure 13. Summer half year (Apr-Sep) precipitation sums 1912-1991 in Havraryd.

To widthen our perspective somewhat we include one annual temperature series from Stykkisholmur on Iceland and a series of annual precipitation from Samnanger in southwestern Norway. The series from Iceland is most probably homogeneous and the one from Norway has been tested thoroughly and found homogeneous. (Homogenous means free from artificial changes due to new instruments, changed nearby surroundings etc).

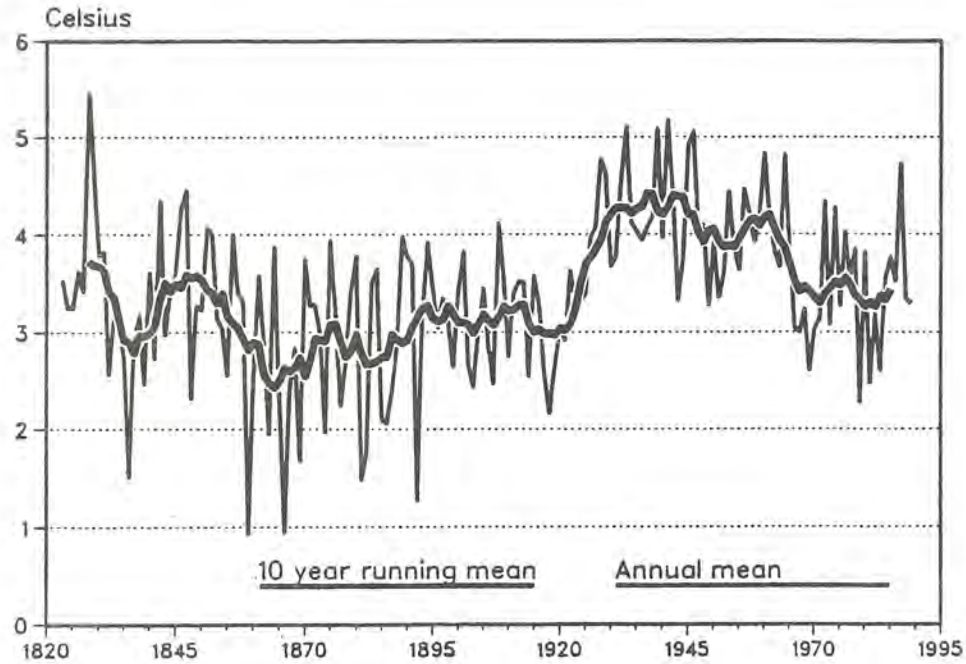


Figure 14. Annual temperature at Stykkisholmur, Iceland, 1823-1989.

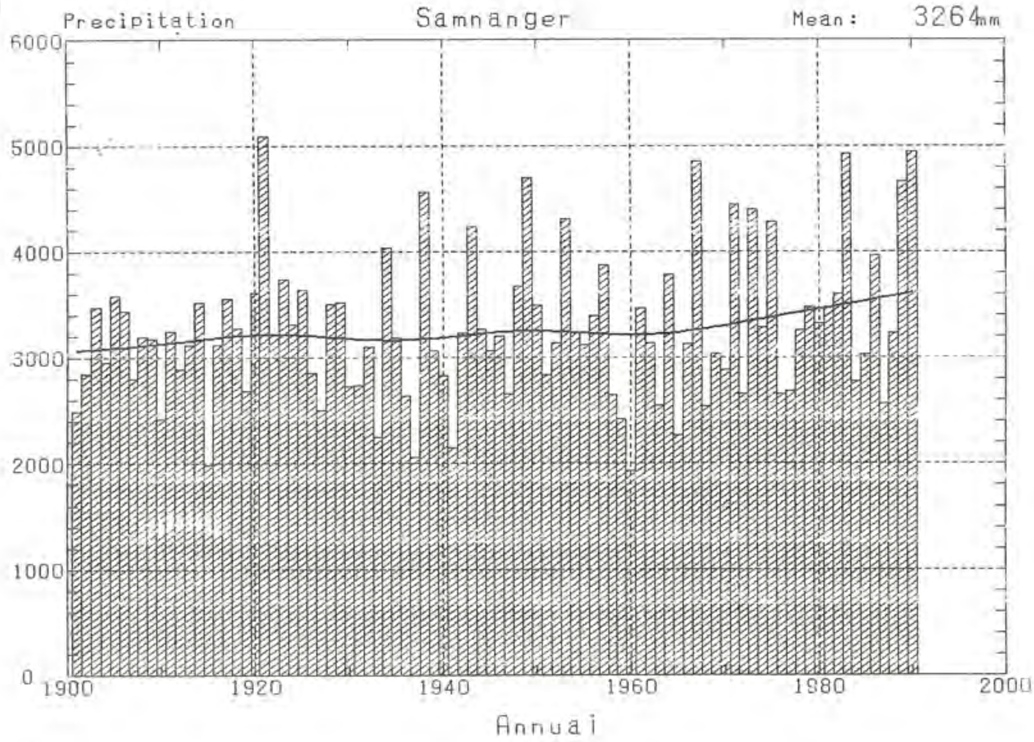


Figure 15. Annual precipitation at Samnanger, Norway, 1901-1990

The overall features of the Icelandic temperature series are similar to Swedish series albeit individual years can be very different. In fact it is quite common that Scandinavia and Iceland are dominated by very different airmasses. But on longer time scales there is a positive correlation between the time series from the two countries.

Samnanger represents one of the wettest regions in Europe and a 'westerly-favoured' site on the steep hills in western Norway. The series indicates a slight increase of annual precipitation during the latest two decades.

The Scandinavian fjells are very important for the precipitation systems. In periods with strong zonal flow on a rather northerly position almost all rain and snow falls on the western slopes while more meridional flow can result in very wet episodes in eastern Sweden and Finland. Thus there is a marked negative correlation on different sides of the fjells on shorter time scales.

The pressure difference between southern and northern Sweden is proportional to the strength of the zonal flow over Scandinavia. The series reveals a decrease around 1930 of about 10%. The more meridional character of the weather when the zonal flow is weaker is also supported by cyclone track studies showing that we have had an increase of low pressure systems coming in from the southern sector (Salomonsson, 1986). This is also in accordance with the reduction of westerly weather types over the British Isles (Lamb, 1977). There is a clear tendency of a recovery of the strength of the zonal flow in the latest one to two decades in Sweden. Several of those years with larger gradients are coupled to mild winters and periods of excessive wetness on westerly slopes.

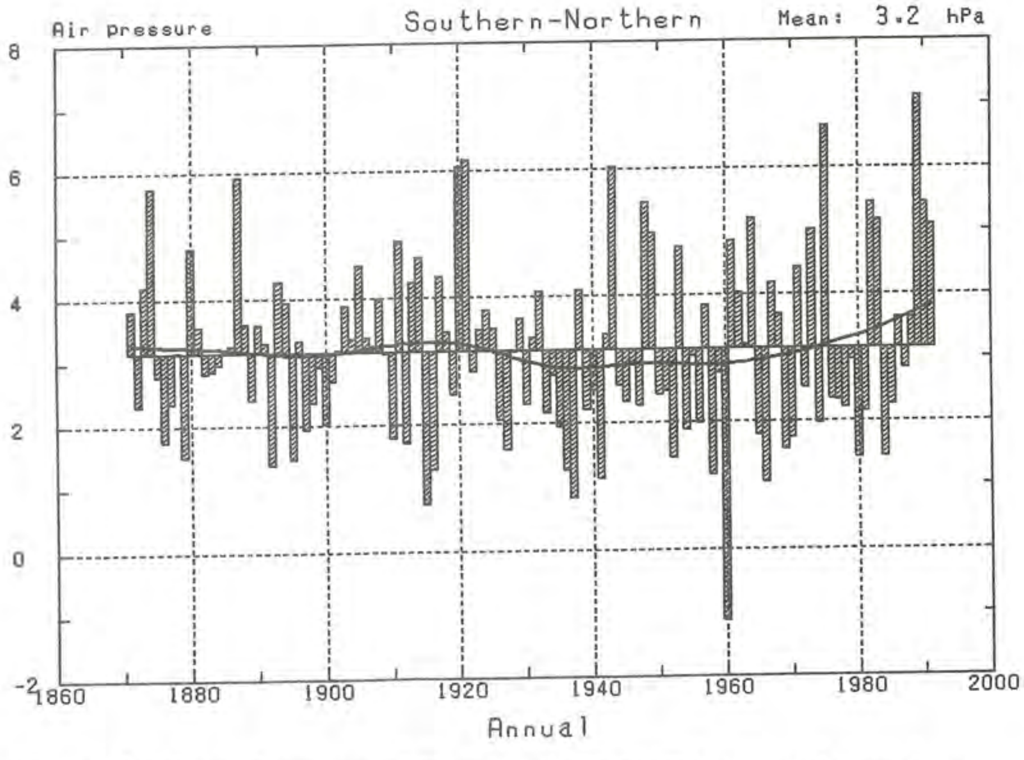


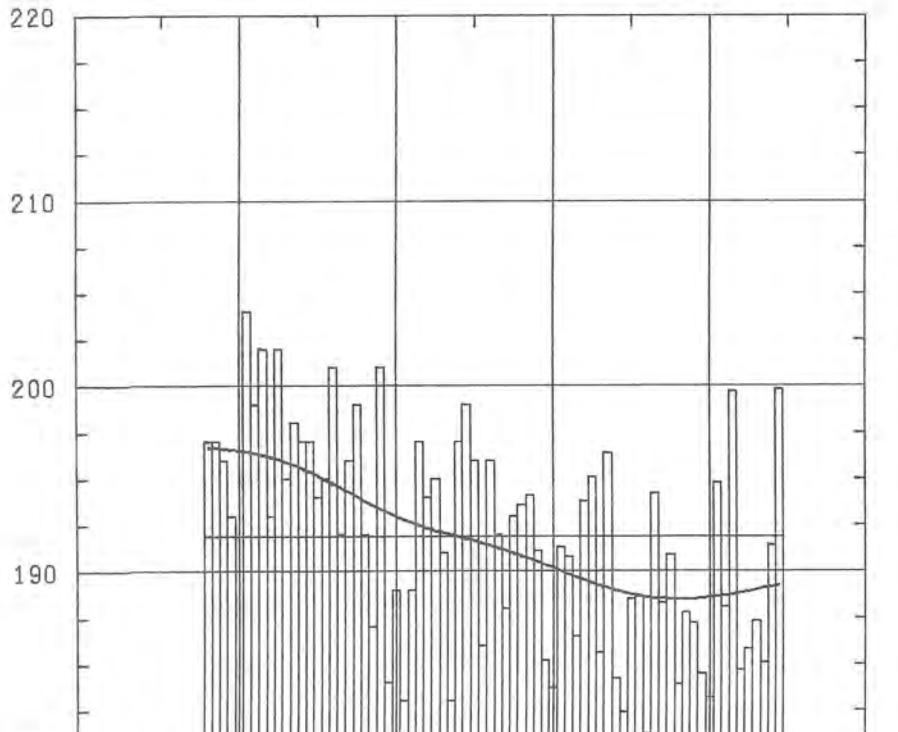
Figure 16. Annual pressure differences 1870-1990 between the southern and northern region - the average zonal (westerly) flow over Scandinavia.

Studies of changes in the circulation patterns over our region can be crucial to get a better understanding of the response to an increase in greenhouse gases. Model studies indicate some poleward shift of cyclone tracks, or at least less winter precipitation in Mediterranean climate zones, but small or no changes in the strength of the westerlies (IPCC, 1990).

The cyclone development within the westerlies is connected with regional zones of temperature and humidity gradients. These zones will probably shift somewhat polewards in a warmer world according to model studies as indicated above.

The final figure in this section shows sea surface levels as measured on Gotland in the Baltic Sea. Due to the isostatic uprise practically the whole of Sweden is lifted up. At most this rise amounts to one centimeter per year but in Skåne it is close to zero. The general downward trend of the water levels at Visby is thus expected but the right end of the curve indicates a slight expansion of the oceans in the latest years - in correspondence with global temperature estimates. The isostatic uprise is a very smooth and practically linear process. Other measurements from Sweden are of the same character.

The result illustrated in Figure 17 can be related to the estimated 10 to 20 cm rise of the global sea surface (IPCC, 1990).



<u>Figure 17.</u> Annual mean water level at Visby, Gotland, Sweden.

There are different ways to extrapolate observed series into the future. Rule number one should rather be not to make any extrapolations at all! But let us mention three alternatives dealing with extrapolation.

1. Extrapolate the "present trend".

2. Assume that cyclic variations exist and decompose the time series into a suitable number of trigonometric terms and extrapolate from that.

3. Consider the long-term average as the most probable state and then if the latest say ten years differs much from this average predict a return to the more normal level. This alternative is realistic for many natural processes in quasi equilibrium systems.

Perhaps rule number three is to prefer if we cannot see any physical explanation for the observed latest trend but rule number one if there is a reasonable coupling to an underlying factor that is changing.

Thus it is easier to accept an upward temperature trend and perhaps also an increase in winter precipitaion in Scandinavia as model runs have predicted such changes. On the other hand the rise in temperature up to about 1940 should rather be a natural, random fluctuation which, according to rule number three, most probably is followed by a return to less favourable temperature conditions.

4 Computer simulations of the future climate

Global climate models are numerical models that are based on the same principals as the weather forecast models. They are based on mathematical formulations of the processes going on in the atmosphere, the oceans and the land surfaces and they are based on the classical physical laws - the conservation of angular momentum, mass and energy of the atmosphere and the oceans. A three-dimensional grid of points with global coverage is used for the computations. Generally, the differential equations are solved using spectral representation. A large number of computations are carried out at each time step (around half an hour). The spatial distance between each grid point is 300 - 600 km in today's climate models. Typical models have between 5 to 20 vertical levels.

The power of the super computers of today puts limitations on the formulation of the present global climate models and in the resolution in time and space of the models. A simulation of the future climate during the coming century by use of a supercomputer can take several months to achieve.

When using the climate models, it is generally assumed that the earth's climate will move to a long-term equilibrium state, in which there is no further change of the system. If the concentration of greenhouse gases is increased then the system will adjust slowly towards a new equilibrium state. The transition period, during which the concentration of the greenhouse gases is gradually changed, is frequently referred to as a 'transient' or 'time-dependent' climate change. The difference between the initial and the final states is the equilibrium climate change.

The main features of the present climate can be reproduced relatively well with global climate models except for some biases that appear in long climate runs. These biases are, however, taken into account in a crude way by subtracting control runs from the experiment runs. Part of the skill is connected with the prescribed conditions which are used in the models, concerning for instance the ocean temperature and the sea ice. The large scale distribution of air pressure, temperature, wind and precipitation obtained from the simulations agrees roughly with reality. On a regional scale there are, however, large discrepancies from the present climate. Typical differences in the regional temperature climate between models and reality are about 3 degrees. In precipitation amount the corresponding differences can frequently be about 50% of the observed precipitation quantity.

The coupling between the processes in the oceans and in the atmosphere are rather rudimentary in present models. In most global climate models only the upper part of the oceans (the so called 'mixed layer') have been represented.

Presently, large flux corrections at the sea surface have to be applied. The flux means here the exchange of heat and water vapour between air and sea. The corrections are of the same order as the fluxes themselves.

It is clear that for simulations 100 years ahead it is necessary also to include the deeper parts of the oceans in the models. In some of the models, for instance the one at the Max-Planck Institute für Meteorologie (Cubasch et al, 1991), also the deeper parts of the oceans have been included.

The main result from computer simulations is a rather strong increase in temperature with the largest rises close to the poles and during winter. The global temperature increase predicted agrees reasonably well with what was obtained at an early stage with simple one-dimensional radiation models.

Today intense global climate modelling activities are going on to improve the parameterization of relevant physical processes and for improvement of the numerical schemes which the models are using. The capacity of the supercomputers are still in a rapid increasing stage due to the use of more parallell processors. This means that it will be possible to improve the temporal and spatial resolution of the models.

In conclusion this means that the global climate models can be expected to be considerably improved within the next decades.

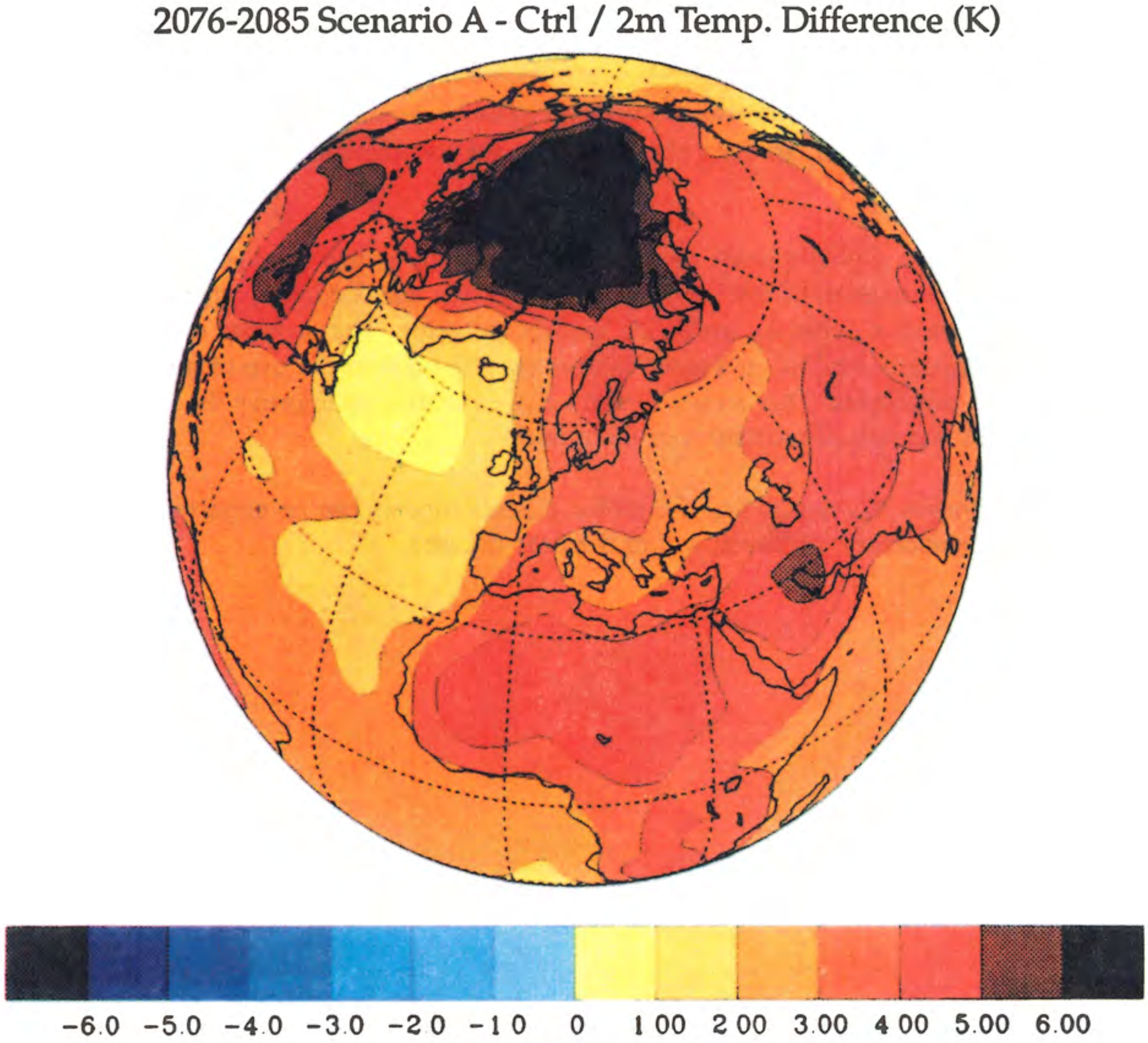


Figure 18. An example of temperature output from a coupled GCM model (developed at the Max Planck institute, Cubasch et al, 1991).

5 Future climate in the Nordic region - synthesis for the next decades

Bearing in mind the considerations in previous sections it is easy to understand that it is a delicate task to interpret model simulations, simpler physical models or present trends into a plausible projection of our future climate in the Nordic region. And what will come out is merely a rather subjective choice among models, articles and the data analysed.

We have collected the scenarios expressed by meteorologists in neighbouring countries (Aune, 1989; Grammeltvedt and Eliassen, 1990; Carter and Holopainen, 1991) without going into any details of these studies. We also include the evaluation given by Rodhe (1990) for the Nordic region (except Iceland). The final column in Table 1 gives our scenario. It is divided into northern and southern Sweden and is given in interval form to express the uncertainty.

Here we also like to add some other studies related to the Nordic countries and to climate change: Alexandersson, 1991; Alexandersson and Eriksson, 1989; Cappelen, 1991; Dahlström, 1991; Frich, 1991; Førland et al, 1991; Hanssen-Bauer, 1991; Heino, 1989; Heino, 1991; and Jonsson, 1991.

As can be seen from the table we are a bit more conservative in our estimates than most of the other authors. The reason for being more moderate concerning temperature changes is that recent model runs (Cubasch, 1991) indicate a slower response in our region than previous runs and that the observations in later decades point in the same direction, i.e. do not show the same clear increase as the global averages. Also the marked warming during the first decades of this century indicates that we are on a rather high level from which it is not so easy to climb further up.

We don't consider the model results concerning regional changes of precipitation as very reliable. This is quite obvious when different models are compared. Precipitation depends very much on local or regional orography which is poorly resolved by climate models. However, we estimate that the global average precipitation will increase with 5-10%. It is reasonable that in a warmer world the hydrological cycle will speed up. Also most of the models have a tendency to give a slight poleward shift of the main cyclonic activity within the westerlies so that during winter there could be some reduction of the rainfall in the Mediterranean region and some compensating increase in northern Europe. But even if these two changes may be of some significance, regional interpretation of the precipitation is still very difficult as minor changes in circulation frequencies, cyclone tracks etc. are of great importance for regional and local changes.

We mention one impact study (Prentice et.al.,1991) in which tree population dynamics is simulated for three sites in Sweden. Generally a temperature increase favours the growth of common species except for spruce (*Picea*) in the drier parts. In critically dry regions also other species may show slower growth rates. More precipitation favours spruce

(*Picea*) and beech (*Fagus*).

In the next few years we will create a more complete homogenized data base for the Nordic region in order to be able to follow the current changes as closely as possible. We will also take an active part in the research going on at the Max-Planck Institute in Hamburg where transient simulations with coupled atmosphere-ocean models are going on using more refined model formulations.

Table 1. Scenarios for the Nordic area for 2030 as proposed by different authors. Unit: Temperature change from 'to-day's climate expressed in degrees Celsius

Authors and region	Temperature Winter	Temperature Summer	Temperature: Year	Precipitation Winter	Precipitation Summer	Precipitation Year
Aune, 1991 Norway, coastal	1.5			increase	increase	
Aune, 1991 Norway, interior	2	1.5		increase	increase	
Grammeltvedt, 1990, Norway	3 - 4 [1]	2		increase [2]	increase [2]	
Carter and Holopainen, 1991 Finland			1.6			+- 0 % (no change)
Rodhe, 1990, Scandinavia	3[3]	2		30 mm/month	10 mm/month	
Present study,[4] N Scandinavia	0.5 - 1.5	0.0 - 0.5		0 - 15 %	0 - 10 %	
Present study, S Scandinavia	0.0 - 1.0	0.0 - 0.5		0 - 15 %	-5 - +10%	

[1] Somewhat less in coastal areas

[2] More convective precipitation, largest increase in spring

[3] More frequent S and SW winds during winter

[4] Relative to a 10 -year average centered around the year 1990

6 Identification of climate detection factors and illustration of Nordic climate scenarios

Significant features of a colder respective warmer world, large-scale averages. The primary response of the climate system to the enhanced greenhouse effect is expected to be a global warming of the lower layers of the atmosphere. We know that the global warming of ca 0.5 degrees that has occured during the last century may be consistent with the increase of greenhouse gases, but also that this warming can be caused by natural fluctuations inherent with our atmosphere.

A global warming/cooling means also that other climate components than temperature will be affected as for instance indicated by the feedback mechanisms accounted for in section 2. For climate change detection it is thus of interest to identify probable responses in a warmer/colder climate of components such as the sea level, volumes of glaciers etc.

Characteristic features of a colder respective warmer world are illustrated in Table 2. There are interactions between all the physical factors and the table thus represents a rough simplification of the climate system.

The atmospheric water vapour feedback is thought to amplify the global climate response to increased greenhouse gases. When the climate is warming an increased evaporation will take place and the resulting increase of water vapour will then trap more infrared radiation. However, Lindzen (1990) has proposed that climate models overestimate this effect: due to increased convective activity in a warmer climate the upper part of the troposphere will rather be drying than moistening. Lindzen has put the argument forward that changes in upper tropospheric water vapour content are of crucial importance for the radiative budget. Shine and Sinha (1991) have, however, by radiative transfer calculations come to an opposite conclusion: the radiative budget of the Earth is most sensitive to changes in the lower tropospheric water vapour concentrations. Though there might be a drying of the upper troposhere in a warmer climate we have synthesized that the probable outcome for the troposphere is an increasing amount of moisture as indicated in Table 2.

It is generally believed that the moisture content of the atmosphere and precipitation volumes on a global basis are positively correlated. Ramanathan and Collins (1991) have proposed that the atmosphere has a natural thermostat which regulates the temperature on the planet: during warm events, like El Nino, highly reflective cirrus clouds are produced which act like a thermostat, shielding the ocean from solar radiation.

Table 2. **Significant features of a colder respective warmer world, large-scale averages.**

Physical feature	Effect of a colder climate	Effect of a warmer climate
Precipitation	decreasing	increasing
Moisture	decreasing	increasing
Cloudiness	decreasing (?)	increasing (?)
Westwind midlat	moving S	moving N
Arctic ice	increasing	decreasing
Greenland ice	increasing in S Greenland, decreasing in N Greenland	decreasing ?
Antarctic ice	less precipitation over Antarctica	more precipitation over Antarctica
Polar front activity	increasing (?)	decreasing (?)
InterTropical Convergence Zone (ITCZ)	smaller amplitude	larger amplitude
Sea level	lowering	raising
Tropical hurricanes	decreasing in number/disappearing	increasing in number

Main trends indicated by climate indicators
a) Global climate indications

The main trends in the global climate system is indicated by Table 3. The trend of the various physical features are entered according to IPCC (1990). A question mark has been indicated where no definite trend has been possible to synthesize.

It should be noted that it is generally believed that during a relatively warmer climate more snow and ice will be accumulated in Antarctica, mainly due to the fact that the atmosphere can contain more moisture then and consequently increase the snow amount falling over Antarctica. This hypothesis is supported by results of analysis of ice cores from the Antarctic research station Vostok.

Over the past 30 years temperature has gone up by about 2 degrees over the Antarctic Peninisula and the accumulation has increased as much as 25 % during this period. Large uncertainties exist in the present knowledge of the mass budget of the Antarctic ice sheet. Present estimates indicates that both the outflow and the net accumulation are approximately equal to 2000 km^3 of ice per year, or equivalent to about 6 mm of sea level.

Morgan et al (1991) suggest that the Antarctic ice volumes have increased during the latest decades with an accumulation rate that corresponds to a lowering of the sea level of 1 - 2 mm per year.

From Table 3 it is obvious that the global response of the climate system to a high extent is unresolved. It is also evident that much of the global climate indications are in the direction of a warming.

__Table 3.__ **Main trends indicated by climate indicators. Global climate indications**

Physical feature	**Indications by observations**	**Indications by models**	**Inferrence: surface temperature**[4]
Global/hemispheric tropospheric temperature	Increasing	Increasing	+
Stratospheric temperature	Decreasing	Decreasing	+
Ice volume of Antarctica	Increasing		+
Atmospheric moisture	?		?
The Northern Hemisphere snow cover	Decreasing (?)		+
Mountain glaciers	Decreasing		+
Sea ice	?		?
Atmospheric Circulation change	?	?	?
Sulphate aerosols	Increasing (?)		- (?)
Other aerosols	?		?
Vulcanic eruptions	?		?
Sea level	Increasing		+
Solar influences	?		?

4 '+' means that the physical feature indicates that the surface temperature probably is warming and '-' means analogously a probable cooling.

b) Regional climate indications - the Nordic area
Regional climate indications for the Nordic area are illustrated in Table 4. In the Table 4 we have entered a rough interpretation of the output from a coupled model from the Max-Planck-Institute as an example of model results for the Nordic area.

It should be emphasized that the behaviour of the arctic ice during a climate change is highly uncertain. Generally recent GCM studies are indicating that the arctic ice will reduce its extent or even be eliminated in a warmer climate. Recently Miller and Vernal(1992) have found observational evidence from proxy data pointing in the opposite direction. They found initial ice sheet growth at the beginning of the last glacial ice cycle occurred at high northern latitudes during climate conditions rather similiar to present.

Table 4. Regional climate indications - the Nordic area

Physical feature	**Indications based on observations**	**Indications based on MPI transient model run (Cubasch et al, 1991)**
Temperature at surface	Decreasing or unchanged after 1940	Increasing over Scandinavia/ Unchanged or decreasing on Iceland and the Norwegian Sea
Precipitation	increasing	Increasing in N Scandinavia
Cloudiness	increasing	?
Arctic sea ice	decreasing (?)	decreasing

From Table 4 there are no definite warming or cooling indications for the Nordic regional area.

Schematic illustration of possible future realizations of the regional climate. To illustrate possible future realizations of the real climate we have constructed some synthetic series representing the annual temperature in northern Sweden with a typical present temperature average of 1°C. These different realizations are obtained as

$$T_i=\sum [\alpha_j \sin(2\times\pi\times i/\omega_j)+\varphi_j]+Z+\overline{T_0}+\Delta T(CO_2)$$

In this formula the summation term represents natural fluctuations (here cyclic for mathematical convenience) with four components with ω_j as 10, 30, 100 and 200 years and α_j as a random amplitude of 0-0.5°C and φ_j as a random phase of 0-2π radians. Further Z is a random number with a standard deviation typical for northern Sweden (1.6°C), T_0 is the present average (1.0°C) and $\Delta T(CO_2)$ is an assumed general rise (0.25°C per decade up to 2030, then 0.33°C per decade).

We hope that this mathematical exercise will give some feeling for typical variations on annual and decadal time scales. But it is of course strongly dependent on our subjective choices, for example of the average trend.

Scenario no 1

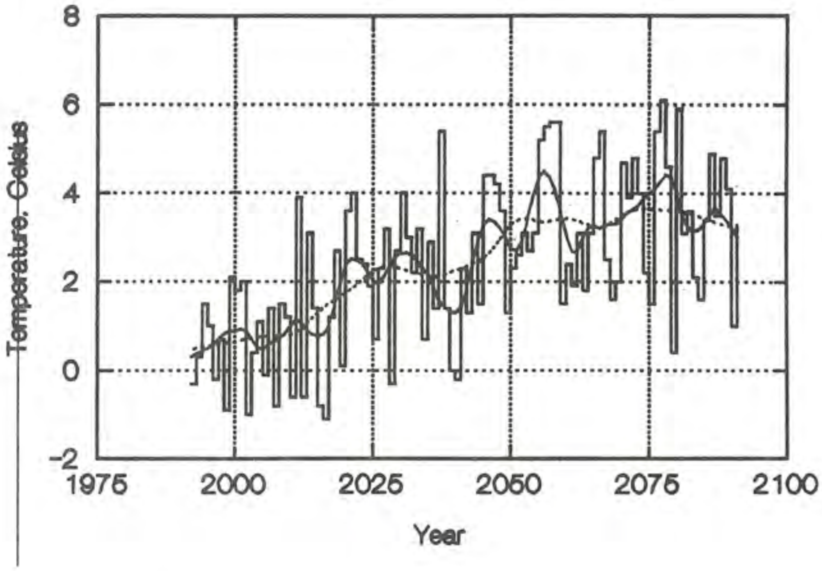


Figure 19: A realization of annual temperatures in northern Sweden according to Eq. 1

Scenario no 2

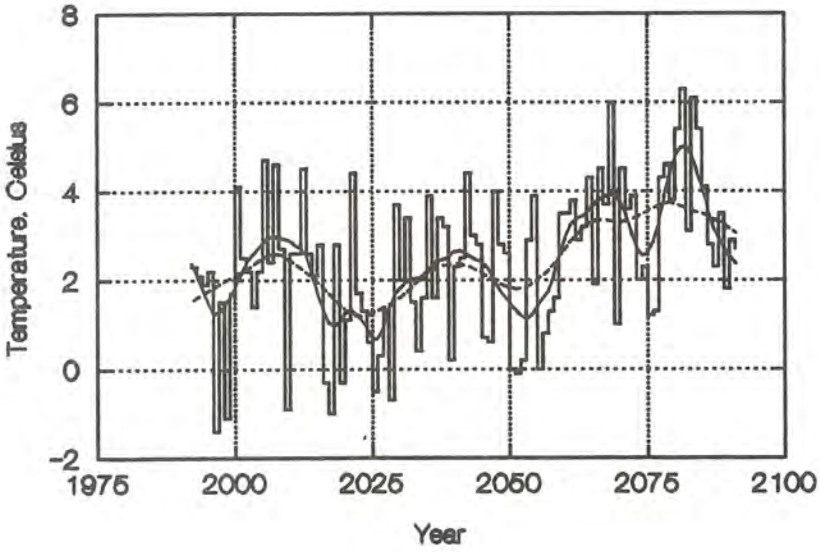


Figure 20: A realization of annual temperatures in northern Sweden according to Eq. 1

Scenario no 3

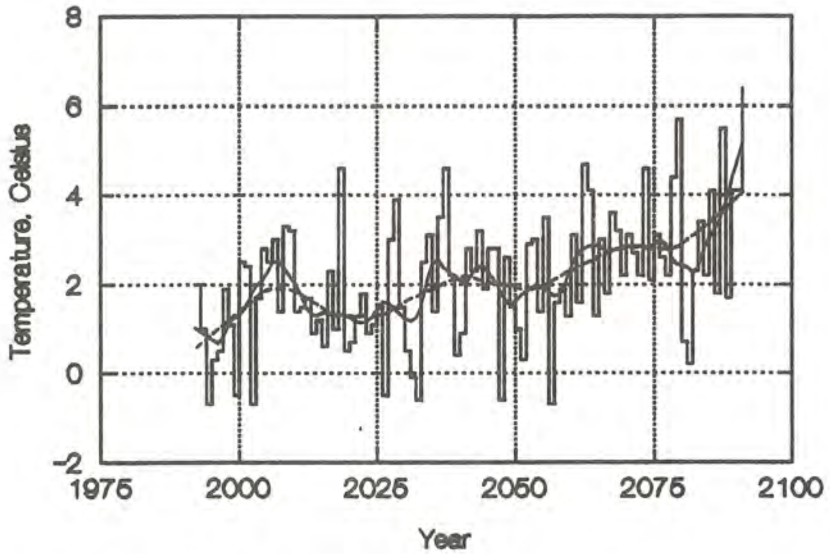


Figure 21: A realization of annual temperatures in northern Sweden according to Eq. 1

Scenario no 4

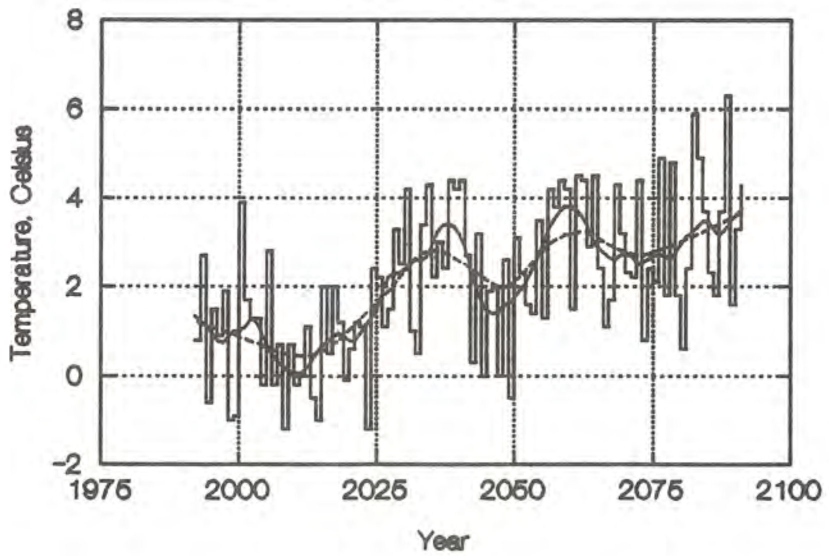


Figure 22: A realization of annual temperatures in northern Sweden according to Eq. 1

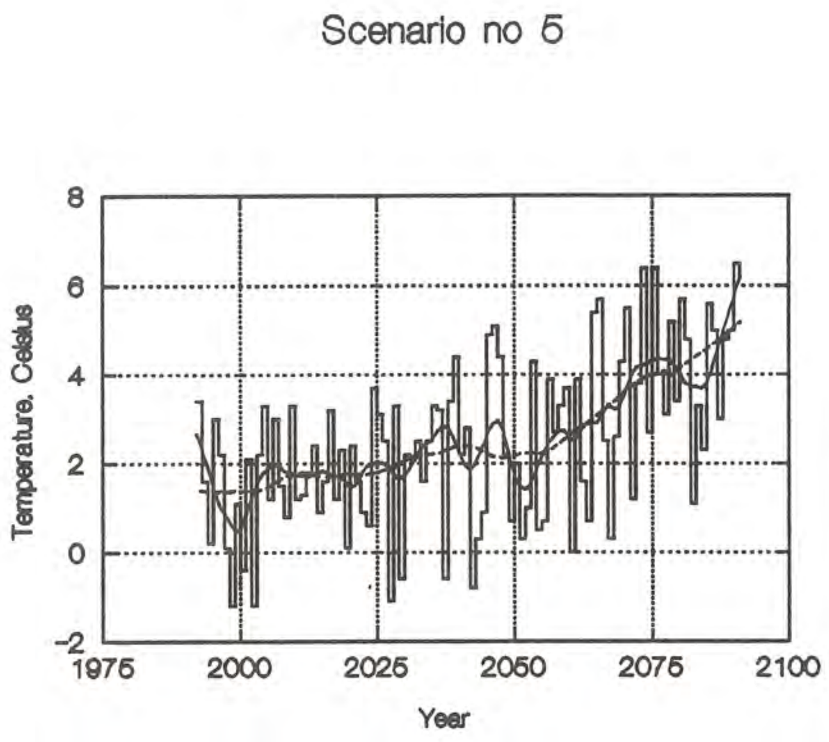
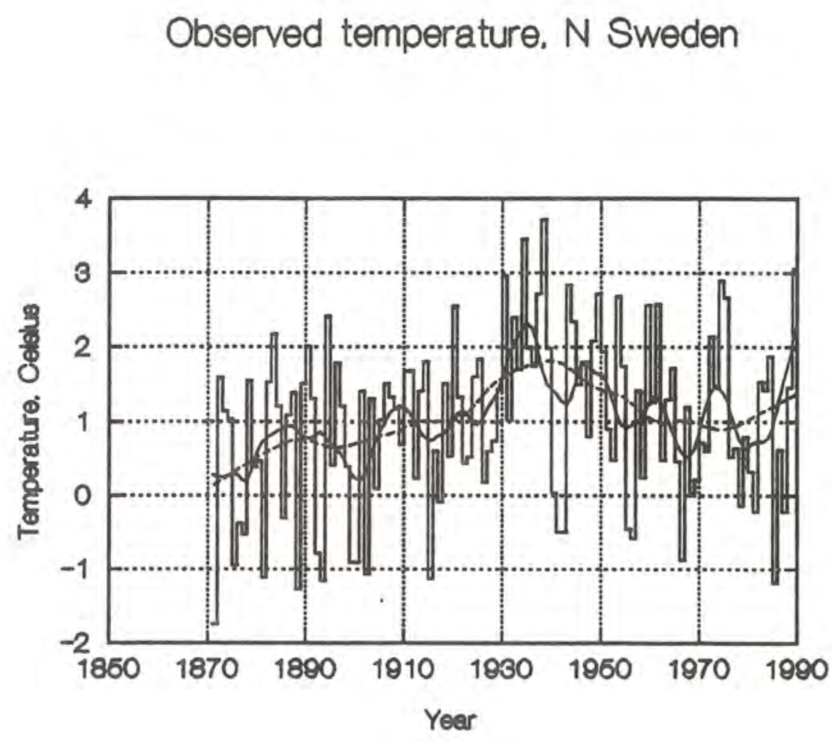


Figure 23: A realization of annual temperatures in northern Sweden according to Eq. 1



7 Main synthesis

The main synthesis is presented in figure 24. The shaded area represents our main scenario of the average temperature trend for the Nordic area exclusive Iceland.

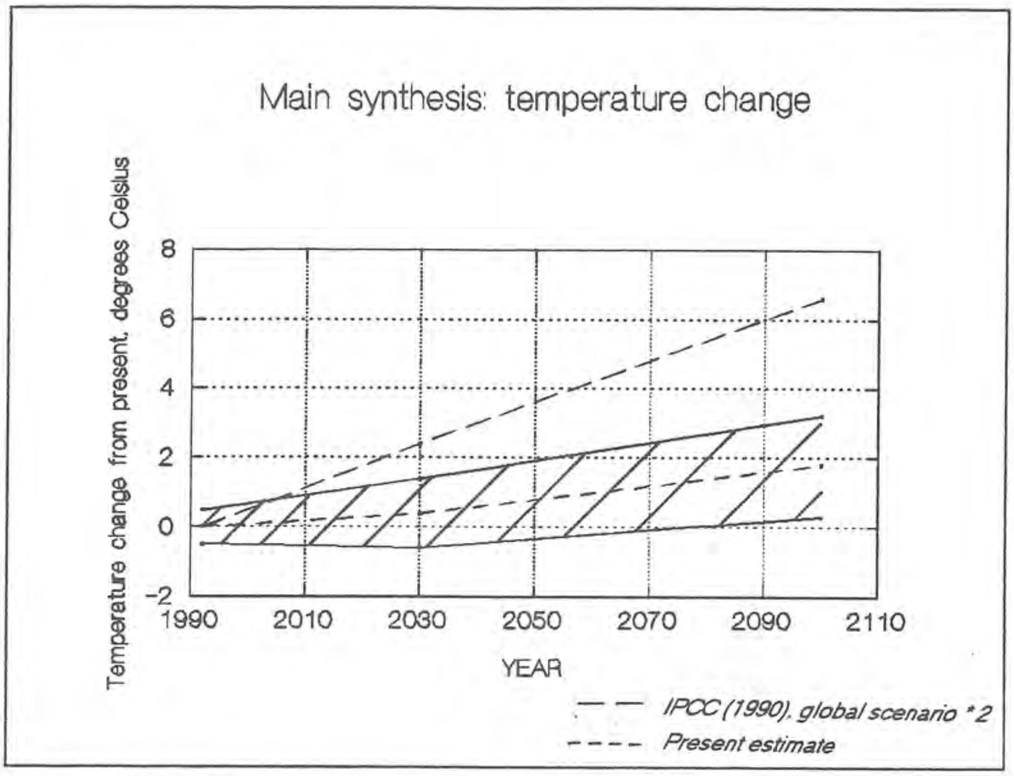


Figure 24: Main synthesis for the Nordic area except Iceland. The shaded area represent an interval to emphasize the uncertainty of the suggested average temperature trend. The shaded area represents the interval within which the future 10-year averages of temperature is expected to fluctuate. The zero-line in the diagram represents the ten-year average centered around the year 1990.

The reasons for the deviation from the interpretated IPCC result (the dashed curve) is mainly connected with the following considerations:

- it seems reasonable that there is a connection between the present climate trends in the Nordic countries and the climate during the next few decades. There are presently no strong indications of a rapid warming.

- the fact that the polar ice still exists and that it has been subjected to only minor changes indicates that the reflected radiation connected with the ice and snow albedos is hitherto relatively unchanged. Much of the warming close to the poles indicated by GCMs represents results of the albedo changes when the ice and snow covered regions are reduced. When/if such a reduction comes it is quite clear that it will play an important role for the Nordic climate. Miller and Vernal(1992) have, as indicated in section 6, recently found observational evidence from proxy data pointing in the direction of Arctic ice sheet growth during warm events, which means the opposite development generally indicated by GCM studies.

- The cloudiness represents another main source of uncertainty.

- Recent climate simulations show less drastic changes in the Nordic area than the earlier ones.

The uncertainty concerning the climate in the Nordic area is not least connected with the following conditions:

- The ocean circulation in the North Atlantic region which is of primary importance for the Nordic climate. The behaviour of the Gulf Stream is particularly important.

We have given our estimates for southern and northern Sweden. Southern Sweden can here represent Götaland, Svealand and also Denmark. Northern Sweden should roughly cover Norrland and also Finland. Western Norway and even more Iceland with their more pronounced maritime climate are thought to be slower in a reaction to a general warming and for Iceland and the Norwegian Sea a corresponding interval could be 0.0 to 0.5 degrees both for winter and summer. On both Iceland and in western Norway it is suspected that winter precipitation will increase.

The results obtained are nothing more or less than a subjective compromise based on a number of considerations and opinions, both from simple and complex modelling and from regional and globally averaged observations.

We believe that research efforts in forthcoming years will give better possibilities to give less uncertain regional scenarios.

Acknowledgement
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