VEÐURSTOFA ÍSLANDS
Icelandic Meteorological Office

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National Energy Authority

CLIMATE CHANGE SCENARIOS FOR THE NORDIC COUNTRIES

a preliminary report

Trausti Jónsson, Tómas Jóhannesson
and Erland Källén

OS-94030/VOD-04B July 1994

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Trausti Jónsson
Veðurstofa Íslands (Icelandic Meteorological Office)
Bústaðavegi 9, IS-150 Reykjavík, Iceland

Tómas Jóhannesson
Orkustofnun (National Energy Authority)
Grensásvegi 9, IS-108 Reykjavík, Iceland

Erland Källén
Danish Meteorological Institute[*]
Lyngbyvej 100, DK-2100 Copenhagen, Denmark

[*] *Present affiliation:*
Department of Meteorology, University of Stockholm,
Arrheniuslaboratory, S-106 91 Stockholm, Sweden

Veðurstofa Íslands (Icelandic Meteorological Office)
Orkustofnun (National Energy Authority)
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ABSTRACT

A climate change scenario for the Nordic countries has been defined by an expert group which was established to estimate future climate changes for use in the Nordic research project *Climate Change and Energy Production*. The scenario specifies a warming rate which increases from 0.3° C per decade for Iceland and the Faeroe Islands to 0.45° C per decade for eastern Finland and the northernmost parts of Sweden. There are marked seasonal and regional differences in the warming rate. Summer warming is predicted to be relatively uniform over the area, ranging from 0.25° C per decade in Iceland and the Faeroe Islands to 0.3° C per decade in Finland. Predicted winter warming is more variable, ranging from 0.35° C per decade in the North Atlantic area to 0.6° C per decade in Finland. Precipitation is predicted to increase by 3-6% per degree of warming, yielding an increase ranging from 1% per decade during the summer season in Finland, Sweden and eastern Norway to 2.5% per decade during the winter season in western Norway. The scenario is primarily based on a subjective evaluation of several recent results from global coupled atmosphere and ocean general circulation models.

Climate in the Nordic countries is characterized by low-frequency natural variability on decadal time-scales which is partly driven by changes in the thermohaline circulation of the North Atlantic. Future behaviour of the North Atlantic ocean circulation is highly uncertain and model predictions of climate development in this part of the world are perhaps more difficult than anywhere else. Other sources of uncertainty in GCM model computations apply to the North Atlantic region as well as to other regions of the world, *e.g.* coarse model resolution, somewhat arbitrary coupling of the ocean and the atmosphere and uncertain parameterizations of clouds and precipitation. In view of these difficulties, the scenario must be considered an extremely uncertain, although plausible, description of what might happen in the future rather than a prediction of what most likely will happen.

1. INTRODUCTION

It is estimated that the global mean surface air temperature of the Earth will rise at a rate on the order of 0.3° C per decade during the next decades due to increasing concentrations of CO_2 and other trace gasses in the atmosphere (IPCC, 1990, 1992). If realized, this warming will have pronounced hydrological effects which are of great economic importance for many sectors of modern industrialized societies. The Nordic research project *Climate Change and Energy Production* (Sælthun, 1992), was started in 1991 by CHIN (Directors of the Hydrological Institutes in the Nordic countries) and KOHYNO (The Nordic Coordinating Committee for Hydrology) with the aim of assessing the hydrological effects of global warming in the Nordic countries with special emphasis on the possible consequences for the operation and planning of hydro-electric power plants.

As a part of this project, an expert group was established to define a consistent climate change scenario for future changes in temperature and precipitation in the Nordic countries. This scenario is used by all subprojects of the main research project in order to maintain internal consistency between the subprojects. The members of the expert group are: Björn Aune (DNMI, chairman), Bengt Dahlström and Hans Alexandersson (SMHI), Raino Heino (FMI), Trausti Jónsson (IMO) and Tómas Jóhannesson (NEA). This report describes the climate scenario which has been defined by the expert group in cooperation with the coordinating committee of the research project. It also summarizes recent research on future climate changes which is of available evidence (observations, palaeoclimate, model output, *etc.*), but it can also be based on more quantitative techniques.

A number of climate scenarios have been defined for the Nordic countries. Early Finnish and Icelandic studies used scenarios based on GCMs model output (GISS-2xCO_2) in addition to temporal and spatial analogue scenarios (Kettunen *et al.*, 1987; Bergthórsson *et al.*, 1987). Aittoniemi (1992) defined three scenarios for 2025 with temperature increase in the range 1.5-6.0° C (winter) and 0.8-3.0° C (summer) and precipitation increase between 10 and 35% in a study of climate change impact on energy production.

The Norwegian climate change assessment (Miljøverndepartementet, 1991) was based on scenarios derived from 2xCO_2 GCM model runs which were assumed to apply around 2020-2050. The "most probable" scenario specified a temperature increase of 1.5-3.5° C and a precipitation increase of 5-15% depending on location (inland/coast) and season. Alexandersson and Dahlström (1992) defined a climate change scenario for Sweden around 2030 which specifies a warming of 0.0-1.5° C and an increase in precipitation of 0-10%, depending on location and season, compared to 1990 values. The Danish climate change assessment (Fenger and Torp, 1992) suggested a temperature increase of 3.5±1.5° C (winter) and 2.0±1.0° C (summer) for Denmark in 2080 and a precipitation increase of around 10-15%. A report by Karlén, Friis-Christensen and Dahlström (1993) published by Elforsk (the Swedish electrical utilities' joint company for research and development) summarizes recent research on climate changes and human influence on climate and raises serious reservations with regard to climate changes scenarios based on GCM results.

The Finnish SILMU project proposed a simple preliminary "best guess" climate change scenario for evaluating potential economic and social impacts of climate change (*e.g.* Carter, 1992). This scenario specifies a warming rate of 0.4° C per decade and a precipitation increase of 3% per decade in winter, but no precipitation increase in summer. SILMU organized a workshop on techniques for developing climatic scenarios in Espoo Finland on 2-4 June 1993 (Carter *et al.*, 1993). A best estimate suggested by the experts at the workshop for the Nordic climate by the year 2100 was: (1) A increase of 3° C in the mean annual temperature with a range of 2-5° C and an east-west gradient with somewhat less warming in the North Atlantic than in Finland. (2) Winter precipitation may increase by a few percent, but summer changes may be positive or negative.

The work of this expert group has primarily focused on recent results from coupled atmosphere and ocean general circulation models. A statistical procedure for deriving future climate at selected Nordic meteorological stations from GCM model output was developed and the results compared to direct model output (Kaas, 1993a,b, 1994). The final scenario is based on a subjective evaluation of available output from coupled atmosphere and ocean general circulation models and the results of the statistical downscaling with some input from historical observations and climatological analogues. The scenario is thus of the composite type as defined above.

A climate change scenario is defined with respect to a climatological baseline which determines a reference point for the projected climate changes. The climatological baseline for the project *Climate Change and Energy Production* is the standard normal period 1961-1990. The scenario specifies changes in temperature and precipitation as these are the most important input variables for hydrological modelling where the scenario will be applied. Hydrological simulations will be performed for time windows centered around 2020, 2050 and 2090 (*i.e.* baseline +30, +60 and particular importance for the derivation of this scenario.

This preliminary report is written by two of the six members of the expert group (Trausti Jónsson and Tómas Jóhannesson) in cooperation with Erland Källén (MISU). They are responsible for the interpretation of the scenario presented here. The discussion of the meteorological research on climate changes is based on their opinions on this subject and may not always reflect the opinions of the other members of the expert group. Any errors or omissions in this report are fully their responsibility. The report will in due course be superseded by a more extensive final report of the expert group now being prepared by Björn Aune of the Norwegian Meteorological Institute.

2. CLIMATE SCENARIOS

A climate change scenario is *not* a prediction of future climate. Rather, it is an internally consistent specification of possible climate development. Climate change scenarios are first and foremost research tools which are used to assess plausible consequences of future climate changes in the absence of reliable predictions of future climate. Climate change scenarios are of several different types, *e.g.* synthetic scenarios, analogue scenarios, scenarios from general circulation models (GCMs) and composite scenarios. (*cf.* Carter *et al.*, 1992, 1993).

Synthetic scenarios are defined by changing climatic elements by an arbitrary amount, often based on a qualitative interpretation of GCM model results. They are useful in many circumstances, but have the drawback that the adjustments may not be physically plausible or consistent. Therefore, synthetic scenarios are in general not recommended except for sensitivity analysis (Carter *et al.*, 1992). These drawbacks may be partially eliminated by basing the adjustments on an evaluation of GCM results, meteorological observations or climatological analogues in which case the resulting scenario will be more akin to a composite scenario as described below.

Analogue scenarios can be subdivided into historical instrumentally-based scenarios, palaeoclimatic analogues and spatial analogues. They have the main advantage that they correspond to *real* climate conditions, past or present. Conditions which determine future climate are, however, likely to be fundamentally different from the conditions that shaped the analogue climate. Differences between the present climate and the analogue climate may, therefore, provide a misleading indication of the nature of future climate changes. In spite of these difficulties, climatological analogues provide important evidence for derivation of composite climate change scenarios.

Scenarios from general circulation models are derived from the output of GCM model runs corresponding to increased concentrations of CO_2 and other trace gasses in the atmosphere. GCMs attempt to simulate the physical processes that determine global climate. They are, in spite of various difficulties, the only method which can be used for tracking the complex interactions between changes in the radiative forcing and the circulation of the atmosphere and ocean which will determine future climate development. Scenarios from general circulation models can be based on direct model output or derived by more sophisticated techniques as further described below.

Composite scenarios are derived by combining some of the above methods or output from more than one GCM. Sometimes the combination is based primarily on subjective evaluation of

+100 years). Preliminary results of the simulations for 25 Nordic catchments are described by Sælthun *et al.* (1994a, 1994b).

3. NATURAL CLIMATE VARIABILITY

The climate of the Earth is characterized by natural variability on all time-scales ranging from the diurnal cycle to millions of years. Variability on the longest time-scales (>1000 years) is related to changes in solar radiation, the configuration of continents and oceans, time-dependent changes in the orbit of the Earth around the Sun (precession, obliquity, eccentricity), and changes in the chemical composition and optical properties of the atmosphere. Variability on a few year time-scale appears to be dominated by natural variability of the atmosphere, but variability on decadal and century long time-scales is most likely caused by the internal variability of the coupled ocean-atmosphere system, and most recently by human influence. Climate changes caused by increasing concentrations of CO_2 and other trace gasses in the atmosphere during the next decades will be superimposed on the natural variability of the ocean-atmosphere system. This prevents an unequivocal detection of predicted greenhouse warming until the temperature has risen significantly above the range of the climatological variability.

Global mean surface air temperature of the Earth has increased by 0.3-0.6° C in the course of the last 100 years (IPCC, 1992). This warming is consistent with transient climate model predictions, but it is also of the same magnitude as natural climate variability.

Climate variability on decadal time-scales is larger in the North Atlantic region than in most other regions of the Earth. Temperature in the North Atlantic region over the last 100 years has fluctuated by as much as 1.0-1.5° C (10 year means), but the variation of temperature with time has been far from a uniform rise. In the decades 1961-1990, a relatively strong cooling trend dominated the climate development in the North Atlantic region (Chapman and Walsh, 1993). The maximum of the cooling (≈0.5° C) was located south and west of Iceland and Greenland, but the cooling extended over most of the North Atlantic Ocean and Scandinavia. The amplitude and spatial distribution of the observed cooling is surprisingly similar to modelled temperature fluctuations arising randomly in this region on a time-scale of approximately 50 years in coupled ocean-atmosphere general circulation models (Delworth *et al.*, 1993; Weisse *et al.*, 1993). The model computations indicate that variability on decadal and longer time-scales in the North Atlantic region is highly influenced by variations in the thermohaline circulation of the North Atlantic Ocean which are related to the so-called North Atlantic Oscillation (*cf.* Lamb and Peppler, 1987). The thermohaline circulation in the North Atlantic Ocean is a part of a larger circulation system, the so-called "conveyor belt". Deep-water formed in the North Atlantic sinks, flows southward and into the Pacific, via the Southern Circumpolar Ocean. It upwells in the North Pacific and is carried back into the Atlantic in the upper ocean. The "conveyor belt" is thought to have played a major role in the extreme climate fluctuations of the last ice age (Broecker *et al.*, 1985). The thermohaline circulation of the oceans is believed to operate in at least two semi-steady states, one with deep water formation taking place in the North Atlantic as described above, and the other without this deep water formation (*e.g.* Källén and Huang, 1987). These different steady states arise "naturally" in coupled ocean-atmosphere GCMs, and the GCM experiments indicate that temperature in the North Atlantic region would be up to 8° C lower without the northward heat transport associated with the deep water formation (Manabe and Stouffer, 1988). An understanding of the dynamics of the thermohaline circulation appears to be vital for assessing greenhouse induced temperature changes in the North Atlantic region, but the dynamics of the thermohaline circulation are still not adequately described in present day ocean models.

It appears likely that the climate system of the North Atlantic region is currently returning from the relatively cool period between 1961 and 1990. If this conceivable "natural" return to warmer conditions has a similar amplitude and time-scale as the recent cool period, then the associated "natural" climate fluctuation will be of a similar magnitude as the warming implied by most climate change scenarios derived from GCMs for this region in the next decades. Transient coupled ocean-atmosphere general circulation models indicate, furthermore, that climate changes due to increasing concentrations of CO_2 and other trace gasses in the atmosphere might lead to significant changes in the thermohaline circulation of the North Atlantic Ocean. The large natural variability of the thermohaline circulation on decadal time-scales and the complex coupling between this circulation and conceivable CO_2 induced climate warming in the North Atlantic region will make it very difficult to differentiate human influence on the climate system from natural climate variability in this region for the next 20-30 years.

4. GLOBAL CLIMATE CHANGE PREDICTED BY GENERAL CIRCULATION MODELS

4.1 Introduction

Studies of global warming using general circulation models have improved dramatically in the last few years as GCMs have become more sophisticated both physically and computationally. The ability of the models to simulate present climate on large scales has improved and methods are being developed to simulate regional climate. This section describes the model predictions on a global scale. Regional climate predictions are discussed in the following section.

Modern GCMs, which are used for climate change studies, have a horizontal resolution of approximately 3°x3° and 10-20 vertical levels. The oceanic part of coupled models has similar or slightly coarser resolution. Sub-grid scale physical processes, such as cloud formation, precipitation, turbulent mixing, gravity wave drag, and vertical mixing in the oceans, are parameterized.

GCM computations of global warming have traditionally been presented in terms of the equilibrium sensitivity of global mean surface temperature to doubling of the effective CO_2 content of the atmosphere. This sensitivity can be computed relatively efficiently by a GCM by instantaneously doubling the effective CO_2 content of the atmosphere and integrating the GCM forward in time to a new steady state. The GCM output describes the large scale geographical distribution of the equilibrium warming and other climate changes in some detail. The global sensitivity encapsulates an important aspect of the predicted climate change, but it does not say anything about the geographical distribution of the warming. Furthermore, it does not describe the temporal evolution of the warming corresponding to the actual gradual increase in the effective CO_2 content of the atmosphere. Nevertheless, the global sensitivity is an important indicator of the potential global warming which might eventually be caused by the increasing concentration of CO_2 and other trace gasses in the atmosphere.

The major advances in GCM studies of global warming in the past few years have been transient simulations and coupled ocean-atmosphere models. Transient simulations describe the temporal evolution of the climate of the Earth as the effective CO_2 content of the atmosphere is gradually increased, typically at an annual rate close to 1%. Coupled ocean-atmosphere models consist of two components, an atmospheric component and an oceanic component which are coupled together by the fluxes of heat, water, and momentum through the surface of the ocean. The coupled models have shown that it is very important to include the ocean dynamics in order to determine the regional distribution of climatic warming. However, this coupling does not produce realistic climate unless so-called flux adjustments are applied. The flux adjustments modify the computed fluxes of heat and vapour through the surface of the ocean in order to produce realistic climatology in a control run. In spite of these advances, confidence in regional climate predictions based directly on the output of the most advanced, coupled, transient GCM simulations remains low.

A comparison of a large number of GCMs is presented by Boer *et al.* (1992), who assess the ability of the models to simulate the present climate, and by Randall *et al.* (1992), who compare the response of the surface energy budget and the hydrological cycle of the models to an imposed sea surface temperature perturbation. An intercomparison of recent coupled ocean-atmosphere models at the regional level is being carried out at the Max-Planck Institute in Hamburg by the IPCC. The results of this intercomparison will be available later in this year.

4.2 Mixed layer models

Until recently, GCM studies of the greenhouse effect have been carried out using an extremely simple representation of the world's oceans. Consequently, the dynamic interaction of the atmosphere and the oceans is far from realistic in these studies. The ocean is modeled as a well mixed layer with thickness on the order of 50 m. Horizontal oceanic heat transport is most often prescribed and remains unchanged during the simulations. Heat exchange with the deeper ocean is either prescribed or computed from an effective heat diffusion coefficient between the mixed layer and the deeper ocean. An example of such a study is Hansen *et al.* (1988) who reference a number of similar studies. The main conclusions of these studies are:

1. The equilibrium sensitivity of global mean surface temperature to a doubling of the effective CO_2 content of the atmosphere is between 2 and 5° C.
2. Transient warming, when concentration of greenhouse gasses in the atmosphere increases by about 1% per year, is on the order of 0.3° C per decade. This rate is often not established until after a few decades of somewhat slower warming.
3. The warming increases more or less uniformly towards the poles. The warming north of 60 °N and south of 60 °S is about the double of the warming close to the equator.
4. Away from the equator, the warming is greater during the winter than during the summer.

The mixed layer GCMs represent the geographical variation of the current climate reasonably well, but they underestimate the long term climatic variability, especially on decadal time-scales. The low climatic variability of mixed layer GCMs is related to the extremely simple representation of the oceans which are an important source of climatic variability.

4.3 Coupled ocean-atmosphere models

In coupled ocean-atmosphere models, ocean currents, horizontal and vertical transport of heat and salinity in the ocean, together with heat, vapour and momentum exchange between the atmosphere and the ocean is explicitly computed. The coupled models usually employ flux adjustments in order to maintain a realistic equilibrium state. The flux adjustments are used to correct the fluxes of water and heat at the oceanic surface by an amount that varies geographically but does not change during the simulation. GCM experiments with increased computational resolution are being carried out with the aim of eliminating the need to employ flux adjustments. Transient, coupled GCM simulations have been carried out at:

- National Center for Atmospheric Research, NCAR, Boulder, Colorado (Washington and Mehl, 1989; Mehl, Washington and Karl, 1993)
- Geophysical Fluid Dynamics Laboratory, GFDL, New York (Manabe *et al.*, 1991, 1992)
- Max-Planck-Institut für Meteorologie, MPI, Hamburg (Cubasch *et al.*, 1991, 1992a)
- Hadley Centre, UK Meteorological Office, UKMO, Bracknell (Murphy, 1992)

These simulations are summarized in IPCC (1992) (computational resolution, cloud description, flux adjustments and length of simulation is given for each simulation). The NCAR simulation, which is the only one that does not employ flux corrections, has recently been extended from 30 to 60 years. The other coupled simulations listed above are 100 years long. The control experiments of the models deviate significantly from the real climatology if flux corrections are not used (*cf.* Manabe *et al.*, 1991). The use of flux corrections is, however, problematic in principle and model results must be viewed with some reservations for regions such as the North Atlantic where the magnitude of the flux corrections is similar to the magnitude of the ocean/atmosphere fluxes themselves. The coupled studies have lead to new surprising insights into the dynamics of the oceans and they underscore the importance of ocean-atmosphere interaction for climate changes (*e.g.* Manabe and Stouffer, 1988).

After an initial period of relatively slow warming, which is present in some of the simulations (*e.g.* MPI, NCAR), but not in others (*e.g.* GFDL), the transient warming rate, when concentration of greenhouse gasses in the atmosphere increases by about 1% per year, is approximately 0.3° C per decade for all the models. The NCAR simulation published in Washington and Mehl (1989) is only 30 years long and gives a somewhat lower rate of warming. A recently published 30 year extension of this simulation (Mehl, Washington and Karl, 1993) shows that the rate of warming for years 23 to 60 of the combined simulation is about 0.3° C per decade.

The warming is largest at high latitudes during the winter as was predicted by the mixed layer models. However, the warming is substantially reduced over the Circumpolar Ocean of the Southern Hemisphere and over the northern North Atlantic due to vertical mixing in the ocean. This effect was not present in the mixed layer models. The amplitude of the local minimum in the warming in the northern North Atlantic varies between the models. It is strongest in the MPI model which shows little warming in the area south of Greenland and Iceland at the end of the 100 year long simulation. The GFDL model predicts a warming in the northern North Atlantic which is relatively close to the global average warming and slightly lower than the average warming of other ocean covered areas. This warming is about half of the warming which is predicted by the GFDL model in the latitude range of the northern North Atlantic. The NCAR model does not predict lower warming over the northern North Atlantic compared to other ocean covered areas after the initial 30 period of relatively slow warming is over.

The main conclusions of the coupled GCM studies are:

1. The estimated global climatic sensitivity and the transient warming rate are in agreement with the previous results of mixed layer models, *i.e.* 2-5° C and approximately 0.3° C per decade, respectively.

2. There is less warming over the oceans than over land areas.
3. The spatial pattern of the warming over the globe does not change significantly after the first few decades of the simulations (except perhaps in the NCAR model).

In spite of the general agreement between the coupled models with regard to the above conclusions, there are large discrepancies between the models, especially in regional predictions of the warming. The location and amplitude of the local minima in the warming in the northern North Atlantic and the Circumpolar Ocean of the Southern Hemisphere is different in the different simulations, and local differences in the warming after 50-100 model years are higher than 2-3° C in many places. Predicted changes in precipitation rates are believed to be much more uncertain than predicted temperature changes, although there is some consensus among modellers that precipitation rates will increase on the order of 5% for each degree of warming.

4.4 Radiation and clouds in general circulation models

The energy balance of the earth is to a large extent governed by an interaction between the optical properties of clouds and radiative processes. In addition, clouds are associated with the heating of the lower parts of the atmosphere through sensible and latent heat transports. As a global average, clouds are responsible for 82 Wm^{-2} in terms of latent heat release to the atmosphere and 58 Wm^{-2} in terms of the reflection of short wave incoming solar radiation. About 14 Wm^{-2} of the incoming solar radiation is absorbed by clouds, and the net long-wave effect of clouds, water vapour, ozone, carbon dioxide, and other greenhouse gases gives a surface temperature which is 33 K higher than it would have been without clouds and greenhouse gases. It is difficult to distinguish between the long-wave radiative effects of clouds and the greenhouse gases as the fluxes are not additive but nonlinearly interdependent. By comparing the basic heat fluxes associated with clouds with the total incoming short wave radiative flux (342 Wm^{-2}) one immediately realizes the significance of clouds. A major shortcoming of present day climate models is their inability to model clouds and their radiative properties in a satisfactory manner (IPCC, 1992). A comparison with the net computed direct radiative effects of a doubling of the CO_2 content of the atmosphere (4 Wm^{-2}) also highlights the importance of a correct treatment of clouds and their radiative properties in a climate model.

The standard method of treating clouds in a climate model is to assume that the optical properties are directly related to the relative humidity. This treatment is relatively cheap in terms of the computing power needed to perform a climate simulation, but it has several drawbacks. It is obvious that the liquid water and ice content of a cloud heavily influences radiative transfer calculations and the relative humidity of air is not sufficient to determine the cloud properties. It has been shown that climate simulations are very sensitive to this particular aspect of cloud treatment and Mitchell *et al.* (1989) demonstrate how sensitive the atmospheric response to a doubling of the CO_2 content is to the prescription of clouds. They compare a standard relative humidity scheme with a more sophisticated one in which the cloud water content is calculated explicitly. The sensitivity to a doubling of the CO_2 content was reduced by more than a factor of two when computed as a global average. It has been argued (Lindzen, 1991) that the high cirrus clouds in the tropics are a particular source of sensitivity, both the assumed ice content and the actual form of the ice particles (Takano, 1992) have a very large influence on the radiative fluxes.

In addition to the feedback between clouds and radiation the clouds are also responsible for a large fraction of the heat transport between the surface of the earth and the atmosphere. This is accomplished through latent heat release, a process which must be parameterized in a climate model. The latent heat transport is particularly strong in the tropics and it has been shown that climate models are sensitive to the way in which this parameterization is formulated. Two different ways of formulating the cloud latent heating were compared in a doubling of the CO_2 content type of experiment. The heating found for the two schemes was markedly different, in particular in tropical regions (IPCC, 1990). The experiments differed almost by a factor of two in terms of the tropical temperature anomaly.

Radiative fluxes must also be parameterized in a climate model. The electromagnetic spectrum has to be discretized in a number of wavelength bands, and the absorption and emission rates have to be calculated over finite model layers. The optical properties of the various atmospheric constituents have to be specified as functions of concentrations, air pressure, solar angle *etc.* Radiative flux computations are very computer intensive, and the design of radiative flux computations is a compromise between model efficiency and accuracy. There are many ways of achieving this compromise, and several schemes have been proposed over the years. A comparison between some of the most popular schemes and some very accurate reference calculations has been made by Ellingson *et al.* (1990). They found that the radiative flux computations produce quite a scatter given the same atmospheric background conditions. Given a clear sky with a standard atmospheric vertical temperature profile the standard deviation of the long-wave flux at the surface was as large as 12 Wm^{-2}. This can be compared with the previously mentioned direct radiative effect of a double CO_2 content which is only 4 Wm^{-2}. Recently, similar tests with the radiation schemes used in European GCM's have been performed by Räisänen (1994). Räisänen (1994) also shows the drastic differences which occur in the radiative treatment of clouds with the different radiation schemes.

The various sensitivities discussed in this section may lead one to think that the present day climate models are completely useless for calculating climate sensitivity to, for example, a doubling of the CO_2 content. This is not the case, but one should be very cautious when interpreting the results. The first objective of any climate model is that is must be able to simulate the present climate with reasonable accuracy. Given that the various parameterizations and other approximations in the model give rise to errors, a certain amount of tuning is necessary. This is often accomplished through a variation of diffusion parameters. Horizontal diffusion, in particular, is a very important process in a climate model, and it is mainly included for numerical reasons. Eliasen and Laursen (1990) have shown that alternative ways of formulating this process give markedly different results, and the model climate is very much controlled by the diffusion parameters. One is thus forced to apply some tuning through the horizontal diffusion scheme, and in the tuning process it may well be that errors in various schemes compensate each other. This will still give us a reasonable model climate but the effects it may have on perturbed climate simulations are unpredictable. For this reason, a comparison between different climate scenario computations done with different models is essential, and if all models give similar results one may have added confidence in the result as compared to a simulation with only one climate model. Increases in computing capacity will also give rise to increased confidence in model computations as the model descriptions of various physical processes may become more accurate and thus improve. Added horizontal and vertical resolution will also make it possible to increase the accuracy of, for instance, the radiative flux calculations. Increased computing capacity may furthermore be used to increase the complexity of the cloud description, thereby improving model performance.

4.5 Discussion

Some transient model simulations show a somewhat reduced rate of climatic warming during the first few decades of the simulations. The slow initial warming is believed to be related to a so called "cold start" problem of GCM simulations which leads to an artificial slow rise in the temperature during the first decades of the simulations (Cubasch *et al.*, 1992a; Meehl, Washington and Karl, 1993; Hasselmann *et al.*, 1993; Cubasch *et al.*, 1994). The significance of the initial slow warming for predictions of future climate must be viewed with a certain "starting point" of the increase in the effective CO_2 concentration in the atmosphere in mind. The effective CO_2 concentration of the atmosphere started to increase rapidly around 1960. Some modellers use the year 1958 (when CO_2 measurements at Mauna Loa, Hawaii, were started) as a starting point when discussing the climate changes predicted by their GCMs (*e.g.* Hansen *et al.*, 1988; Stouffer *et al.*, 1989), whereas others (*e.g.* Cubasch *et al.*, 1991, 1992a) use a starting point between 1980 and 1990. The former approach seems more sensible for most currently available coupled GCM simulations which do not take buildup of CO_2 before the start of the computations into account in an explicit way. This implies that the initial period of slow warming predicted by some GCMs should already be over by now and future warming rates should be estimated as the simulated GCM warming after an initial period of approximately 30 years. As mentioned above, the available transient coupled GCM simulations indicate that this warming rate is approximately 0.3° C per decade, which is in agreement with the estimate of IPCC (1990, 1992). Recently, a coupled model experiment starting at an early stage of industrialization, *i.e.* 1935, has been performed (Cubasch *et al.*, 1994), and some authors have begun correcting the results from model runs started with present equivalent CO_2 levels to compensate for the effects of the "cold start" (*cf.* Cubasch *et al.*, 1993). These studies indicate a warming rate close to 0.3° C per decade from 1990 and onwards for transients experiments.

Some coupled ocean-atmosphere GCM simulations indicate that CO_2 induced warming is substantially reduced in the northern North Atlantic region compared to the warming that would occur in this region in the absence of vertical mixing in the ocean. In spite of the low confidence in regional GCM model predictions, this effect seems to be real, and should lead to reduced warming in the Nordic countries. The predicted warming has a minimum south of Iceland or Greenland and increases towards continental Europe. The warming in the northern North Atlantic would be substantially above the global average (by a factor on the order of 1.5-2) in the absence of this effect because the warming generally increases towards the poles. The predicted local minimum in the warming in the northern North Atlantic is not particularly strong in the NCAR simulation, in the GFDL simulations the warming in the northern North Atlantic is similar to the global average, but the local minimum in the warming in the MPI and UKMO simulations is almost zero. In MPI, GFDL and UKMO simulations, the warming in northern Scandinavia and Finland is somewhat above the global average. There seems to be considerably greater uncertainty in the model predictions in and near the northern North Atlantic Ocean than in most other parts of the world.

In view of the great effect of ocean dynamics in coupled ocean-atmosphere GCM simulations on the predicted warming near the North Atlantic, it seems clear that results from mixed layer GCM simulations *cannot* be used to estimate CO_2 induced climate changes in this area. Conclusions based on such models, for example increasing warming towards the poles, higher warming in the winter than in the summer and a greater increase in winter precipitation than in summer precipitation, are therefore not directly applicable when estimating climate changes in this region.

Prediction of CO_2 induced warming in the Nordic countries is even more problematic than in most other countries. Currently available coupled ocean-atmosphere simulations indicate that the rate of CO_2 induced warming might be similar or somewhat lower than a global average of approximately 0.3° C per decade in Iceland, in southern Greenland and along the west coast of Norway and Denmark. The warming in other parts of the Nordic countries could, on the other hand, be somewhat higher than the global average, *i.e.* more in line with other areas in the latitude range of the Nordic countries. The GFDL results indicate that the warming in the northern North Atlantic and in Scandinavia will not be as seasonally dependent as elsewhere in the latitude range of the Nordic countries, *i.e.* the warming will be similar for both summer and winter. Very little can be said about precipitation changes directly on the basis of the output of the coupled GCMs, except that it is likely that precipitation will increase, perhaps by on the order of 5% for each degree of warming. The uncertainty of these predictions can be somewhat reduced by making a regional prediction of surface climate parameters from the free atmosphere GCM results as discussed in the following section.

5. DERIVATION OF REGIONAL CLIMATE CHANGE FROM GENERAL CIRCULATION MODEL OUTPUT

5.1 Introduction

Confidence in regional climate predictions based directly on the output of the most advanced transient coupled GCM simulations remains low in spite of the important improvements in GCM computations in the past few years. However, it is widely accepted that present day GCMs are able to simulate the global large scale state of the atmosphere in a realistic manner. It is estimated that GCM results are unreliable on spatial scales shorter than about 4-8 times the spatial discretization length in the models computations. This corresponds to approximately 2000-4000 km for current GCM simulations. It is desirable to be able to make climate predictions on shorter scales than this, especially in regions where spatial gradients in the predicted climate changes are large and in areas where orographic effects on the climate are important. Both is the case for the Nordic countries.

GCM results can be interpolated to shorter spatial scales using a nested approach (regional climate models driven with the large scale flow) or statistical methods (correlating regional climate with the large scale flow).

5.2 Nested approach

In the nested approach, a regional climate model is driven with the large scale flow predicted by the GCM. This has, among other things, the advantage that the orography of the region under consideration can be represented much more accurately than is possible in the GCM itself. Meteorological processes, which are orographically controlled, *e.g.* orographic precipitation, can thus be much better resolved, which is especially important for accessing the hydrological impact of the predicted climate changes. Examples of studies of this kind are Giorgi *et al.* (1992) and Marinucci and Giorgi (1992).

5.3 Statistical approach

In the statistical approach, empirically determined correlations between the *observed* regional climate and the corresponding *observed* large scale atmospheric flow are used to estimate the regional climate corresponding to the large scale atmospheric flow predicted by the GCM. Examples of studies of this kind are Karl *et al.* (1990), Storch *et al.* (1991) and Hewitson and Crane (1992). These studies show considerable promise in predicting local surface parameters which are unreliable in the unprocessed grid point output of the GCMs. The work of Storch *et al.* (1991) is specifically directed towards predicting regional precipitation. It shows that the simulation of the present climate is very much improved by the statistical considerations, and also that the CO_2 induced precipitation changes predicted by the statistical approach are significantly different from the precipitation changes predicted on the basis of GCM grid point values.

5.4 Discussion

In spite of the considerable promise offered by the downscaling methods discussed above, they depend critically on the quality of the large scale flow predicted by the GCM. Errors due to flux corrections, gravity wave drag, sea ice representation, cloud parameterization and other known problematic aspects of GCMs will influence the downscaled results, although some other problematic aspects, caused by coarse model resolution, unrealistic orography, and omission of various other local effects, will be improved. Therefore, the results from downscaling cannot be considered reliable until significant improvements in the large scale GCM results are realized.

6. CLIMATE CHANGE SCENARIOS FOR CLIMATOLOGICAL STATIONS IN THE NORDIC COUNTRIES

6.1 Introduction

In order to estimate local climate changes in the Nordic region a statistical downscaling study of this region was carried out by Eigil Kaas at the Danish Meteorological Institute (Kaas, 1993a,b, 1994) at the request of the expert scenario committee. Climate changes were computed at 10 climatological stations in the Nordic countries based on coupled ocean-atmosphere results from the Max-Planck Institute in Hamburg. The stations are Tromsø, Bergen, Östersund, Stockholm, Sodankylä, Kuopio, Kirkjubæjarklaustur, Nuuk/Godthåb, Thorshavn and Copenhagen (Fig. 1). The GCM results from MPI were used because they were readily available at the time the study was initiated, and the MPI model appeared to be no better or worse than other coupled GCM models in use at that time.

6.2 The MPI model

The atmospheric component of the model (ECHAM-1) is a low resolution version of the spectral numerical weather forecasting model of the European Centre for Medium Range Weather Forecasts which has been modified at MPI in Hamburg. The horizontal resolution is limited by a triangular spectral cut-off at total wave number 21. The model has 19 vertical levels in a hybrid σ-p-system. The ocean component (LSG) has 11 variably spaced vertical levels and two overlapping 5.6°x5.6° horizontal grids. The atmosphere and ocean components are coupled by the air-sea fluxes of momentum, heat and water using flux-corrections to prevent undesirable drift in the control simulation. Further description of the model is given in Cubasch *et al.* (1992a) and in a number of reports available from MPI.

6.3 The control simulation

The results of the MPI model in the North Atlantic region are compared to observations in Kaas (1993a). It is found that there are large systematic errors in the 500 hPa height and in the mean

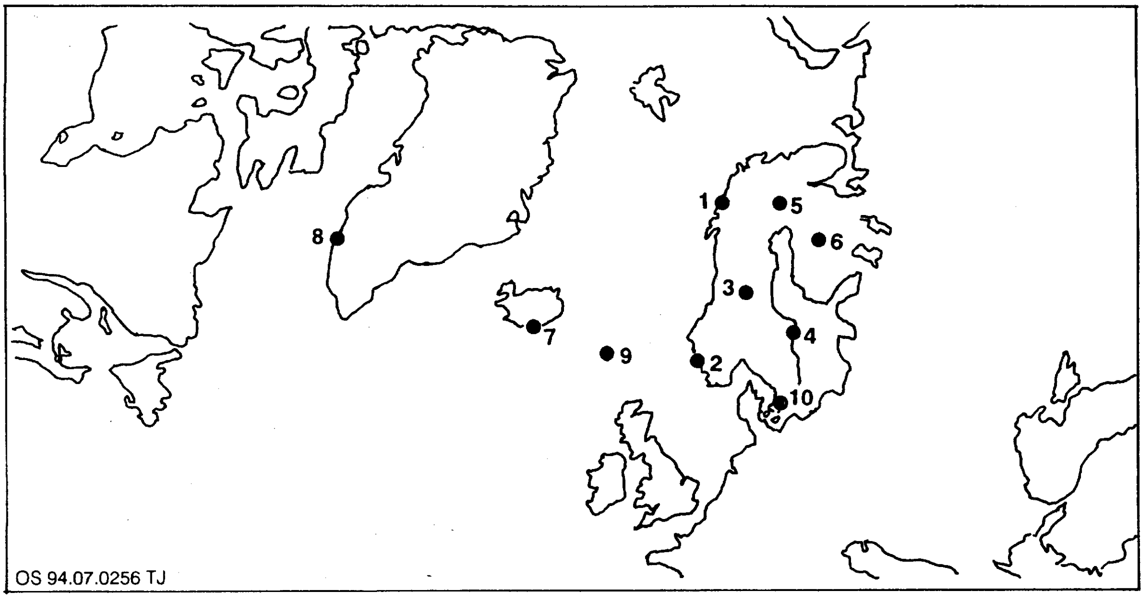

Figure 1: Location map showing the climatological stations used in the statistical analysis. The stations are: 1. Tromsø, 2. Bergen, 3. Östersund, 4. Stockholm, 5. Sodankylä, 6. Kuopio, 7. Kirkjubæjarklaustur, 8. Nuuk/Godthåb, 9. Thorshavn and 10. Copenhagen.

sea level pressure of the control run compared to NMC (US National Meteorological Center) analyses of the North Atlantic region. The 500 hPa height during the winter season in the model has a much too weak north-south gradient and indicates a NW wind direction over most of the region instead of the SW wind direction prevailing in the NMC analyses. The Icelandic low in the model winter sea level pressure field is displaced far to the south-west. Consequently, near-surface wind direction is easterly instead of westerly over much of Europe and the North Atlantic Ocean. It therefore appears that the large scale atmospheric flow in the model in the North Atlantic region is not particularly realistic. This violates the basic assumption of the statistical downscaling technique as described in the previous section. The climotology of the modelled large scale atmospheric flow has become more realistic in recent GCMs with increased computational resolution. Full transient coupled experiments with these models are, however, not available at this time of writing. Although the results of the statistical downscaling described here must be viewed with some reservations due to the abovementioned deficiencies of the control climatology, the statistical method is sound and will produce more reliable results when applied to improved GCM simulations as they become available. The statistical analysis was nevertheless carried out in order to see whether climate changes predicted by the downscaling would differ much from changes derived directly from grid point values. A comparison of the Arctic climate of five atmospheric GCMS (Walsh and Crane, 1992) indicates that other GCMs which have been used for climate change experiments are inflicted with similar problems in the North Atlantic region, although the GFDL model appears to perform significantly better than the other models in this area.

6.4 Statistical method

The statistical method is based on a regression analysis which relates observed monthly mean values of meteorological variables at climatological stations to an EOF decomposition of the monthly mean large scale atmospheric flow (Kaas, 1993b). The predictive variables are 500 hPa heights or the average of the 500 and 1000 hPa heights (representing pressure) and 500/1000 hPa thickness (representing temperature) from NMC analyses in the time period 1961-1987. The regression explains 90-95% of the variance of observed mean monthly winter temperatures and 80-95% of the variance of the summer temperatures. Precipitation was more difficult to reproduce: the regression explains 70-90% and 50-80% of the observed variance in the winter and summer precipitation, respectively.

The regression model, which has been derived from station and NMC observations, is applied to predicted *circulation changes* from the last 30 years of the MPI model runs (*i.e.* transient-control). This procedure yields statistical estimates of changes in modelled predictands at the stations, *e.g.* surface temperature and precipitation. The 30 year period is centered around year 85 of the transient run. Therefore, the estimates apply to approximately the middle of the next century if one assumes that the "cold start" problem leads to a 20-25 year retardation of the MPI model response.

6.5 Downscaling results

Results of the statistical downscaling for temperature and precipitation changes for the 10 Nordic climatological stations are summarized in Table I below. The table lists the results for the summer and winter seasons only. Kaas (1993b, 1994) gives full results for all four seasons of the year, including predicted changes in the diurnal temperature range which are omitted below. Temperature changes are given in ° C and precipitation in percentages. Kaas derived two sets of predicted changes with slightly different statistical methods. In Kaas (1993b), the 500 hPa height and the 500/1000 hPa thickness are used as predictors and the statistical analysis is performed independently for each season of the year. In Kaas (1994), the average of the 500 and 1000 hPa heights (instead of the 500 hPa height) and the 500/1000 hPa thickness are used as predictors and the yearly cycle is removed from the observed predictors and predictands before calculation of the regression coefficients. There are some further differences between the methods which are described in detail in Kaas (1994). The results from Kaas (1993) are indicated with the subscript "1" in the table and the later results of Kaas (1994) are indicated with the subscript "2".

TABLE I: Temperature and precipitation changes predicted by statistical downscaling of transient GCM output from MPI for 10 Nordic climatological stations. The changes correspond to approximately the middle of the next century and they should be interpreted with respect to a 1961-1990 baseline.

Station	**Temperature**				**Precipitation**			
	Winter		Summer		Winter		Summer	
	ΔT_1 (°C)	ΔT_2 (°C)	ΔT_1 (°C)	ΔT_2 (°C)	ΔP_1 (%)	ΔP_2 (%)	ΔP_1 (%)	ΔP_2 (%)
Tromsø	4.2	4.7	2.8	2.3	38	28	40	51
Bergen	3.4	3.5	1.2	0.5	30	29	17	26
Östersund	5.7	7.3	1.6	3.0	8	-42	8	-11
Stockholm	5.5	5.7	1.2	3.3	43	-30	20	-10
Sodankylä	7.2	9.0	1.5	4.1	-19	0	5	-5
Kuopio	6.7	6.9	1.7	4.1	37	-9	24	22
Kirkjubæjarklaustur	1.7	2.2	1.3	0.2	4	64	20	53
Nuuk/Godthåb	2.0	-3.3	1.1	-2.1	9	8	13	79
Thorshavn	2.1	2.7	1.3	0.9	20	1	-4	0
Copenhagen	3.1	2.8	1.5	2.1	6	-38	-4	-64

Kaas (1994) applied a Monte Carlo technique to estimate a standard deviation of his statistically computed changes. This standard deviation is an estimate of the effect of statistical uncertainty in the regression coefficients on the predicted climate changes. Uncertainty in the long term mean difference between the transient and control runs of the climate model is, however, not accounted for. More importantly, uncertainty due to the unrealistic large-scale flow of the climate model is not included in this standard deviation. The standard deviations vary between the stations. They are 0.5-2° C for the temperature changes, but for the precipitation changes they are on the same order as the predicted precipitation changes themselves.

6.6 Discussion

With the exception of ΔT_2 for Nuuk/Godthåb, the downscaled temperature changes are in relatively good agreement with grid point values from coupled ocean-atmosphere GCMs in this region. This agreement shows that surface temperature changes derived from GCM grid point values are in fact fairly consistent with predicted changes in the large scale atmospheric flow. Temperature changes during the winter are greatest in Finland and in northern Norway and Sweden, but smaller in Greenland, Iceland and the Faeroe Islands. Temperature changes in the summer season are smaller and more uniform over the region. The corresponding warming rates are approximately 0.2-0.3° C per decade during the summer season when retardation due to "cold start" is taken into account. During the winter season, the warming rates vary from approximately 0.3° C per decade in western part of the area to over 1° C per decade in the eastern part. The negative ΔT_2 values for Nuuk/Godthåb are difficult to explain, but it appears that the regression model for Nuuk/Godthåb is not as well determined as for the other stations (Kaas, personal communication) and the negative changes there are probably not significant. The differences between the changes computed by the two methods are not great (except for ΔT_2 for Nuuk/Godthåb) and we are inclined to take them as indicators of the uncertainty of the methods, rather than preferring one method to the other.

The precipitation changes vary strongly from station to station and from season to season as would be expected from the high values of the statistically determined standard deviations of the estimated changes. On average the relative increase in precipitation is positive by on the order of 10% which is similar to the zonally averaged increase in precipitation at the latitude of the Nordic countries according to some coupled ocean-atmosphere GCMs (*e.g.* Manabe *et al.*, 1991). Irregular distribution of predicted changes in precipitation are not uncommon in climate change studies (*e.g.* Marinucci and Giorgi, 1992), and are partially due to the inherent internal variability of precipitation which is to some extent reflected in the model results. It is difficult to draw any firm conclusions about future changes in precipitation from these results. Therefore, precipitation changes are highly uncertain, but they may be slightly positive when averaged over long time periods and large areas.

7. CLIMATE CHANGE SCENARIOS FOR THE NORDIC COUNTRIES

Due to the serious errors in the predicted large scale flow of the MPI model, it is not clear that the downscaled climate changes described in the previous section are more realistic than changes derived directly from grid point values. The scenario recommended by the expert group is therefore not based directly on the statistically derived climate changes. The expert group decided to derive the climate change scenario by subjective evaluation of available coupled ocean-atmosphere GCM results and the statistical downscaling results. Relatively great emphasis is put on the results from the GFDL model in this evaluation because it seems to perform better than other models in the North Atlantic area (Walsh and Crane, 1992).

The downscaled summer warming agrees relatively well with GCM results, except that the GFDL model predicts a somewhat higher warming over the North Atlantic ocean than is derived by the statistical procedure. The downscaled winter warming in Finland and Scandinavia is, on the other hand, somewhat greater than predicted by the GDFL model in that area. The scenario specifies an annual warming rate of 0.3° C (0.35° C in winter and 0.25° C in summer) for the western part of the area, increasing to 0.45° C (0.6° C in winter and 0.3° C in summer) in Finland, northern Norway and Sweden. A sinusoidal variation with time between the summer and winter values is assumed. Figure 2A shows the temperature change scenario. This temperature scenario is roughly in agreement with an average of four different coupled ocean-atmosphere GCMs in the Nordic region (Fortelius *et al.*, 1994; based on Räisänen, in press), except that the west-east gradient in the summer warming is slightly less in the scenario than in the GCM average.

The precipitation scenario is more problematic than the temperature scenario. The expert group has decided to specify precipitation changes as approximately 3-6% per degree of warming, using the lower part of the range in the more continental climates of eastern Norway, in Sweden and Finland, and the higher values along the western coast of Norway where precipitation is primarily controlled by orography. These values are broadly consistent with reported precipitation GCM increases in the latitude range of the Nordic countries (*e.g.* Manabe *et al.*, 1991). The predicted precipitation increases are larger in winter than in summer, in line with GCM results and the precipitation scenarios which have been derived in the Finnish SILMU project. Figure 2B shows the precipitation change scenario.

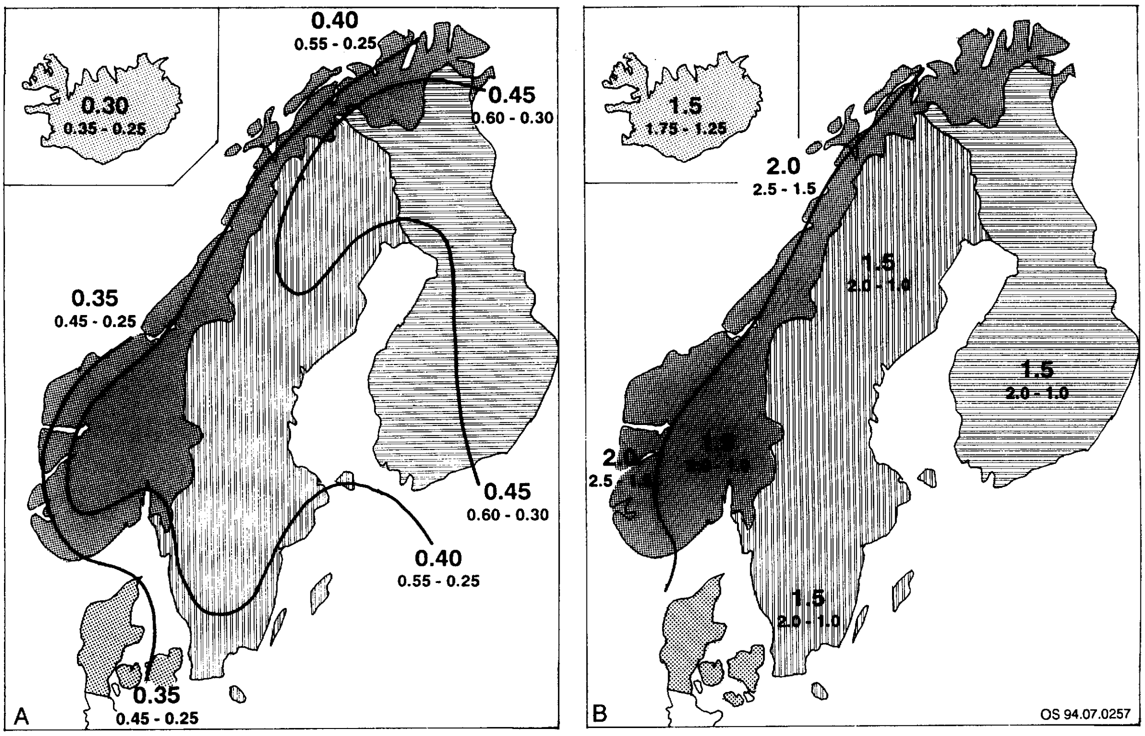

Figure 2: Climate change scenario for the Nordic countries:
(A) Predicted changes in mean surface air temperature, mean annual and winter-summer values, in °C per decade from a 1961-1990 baseline. Changes for the Faeroe Islands are the same as for Iceland and for Nuuk/Godthåb the same as for western Norway.
(B) Predicted changes in precipitation, accumulated annual and winter-summer values, in percent per decade from a 1961-1990 baseline. Changes for the Faeroe Islands are the same as for Iceland and for Nuuk/Godthåb the same as for central Scandinavia.

8. SUMMARY AND CONCLUSIONS

Anthropogenic input of CO_2 and other greenhouse gasses into the atmosphere will lead to significant changes in the radiation budget of the atmosphere in the next decades. The effect of these changes on global and especially on regional climate remains somewhat conjectural in spite of recent advances in the computer models used to estimate future climate changes. Coupled ocean-atmosphere general circulation models are the most sophisticated tools currently available to assess future climate changes in a consistent manner. These models predict an average global warming rate of approximately 0.3° C per decade during the next one hundred years if the current rate of increase in the concentration of greenhouse gasses in the atmosphere continues unabated.

The regional distribution of the predicted climate changes is highly uncertain. Available coupled ocean-atmosphere GCM experiments indicate that warming in the North Atlantic area will be slower than on the continents in the same latitude range due to a reduction in the strength of the thermohaline circulation in the North Atlantic. The models do not represent the regional climate of the Nordic region very well. The derivation of climate change scenarios based directly on GCM model output in this region is therefore not recommended.

A statistical downscaling of GCM model results from the Max-Planck Institute in Hamburg (MPI) was carried out for the Nordic region in order to improve the regional distribution of the predicted climate changes. The statistical method is based on a regression analysis which relates observed monthly mean values of meteorological variables at climatological stations to an EOF decomposition of the monthly mean large scale atmospheric flow. The regression model was applied to predicted circulation changes according to the control and transient runs from MPI in a 30 year period centered around the middle of the next century. Downscaled temperature changes are broadly in agreement with the grid values from coupled GCMs in this region. Temperature changes in the winter are largest in Finland and northern Scandinavia, but smaller on the Atlantic islands. The changes in the summer season are smaller and more uniform. Precipitation changes vary strongly from station to station and from season to season. On the average, the relative increase in the precipitation is positive and on the order of 10%.

Due to serious flaws in the predicted large scale flow of the control run of the MPI model, it is not clear that the downscaled climate changes are more realistic than changes derived directly from grid point values. The expert group therefore decided to derive the climate change scenario by a subjective evaluation of available coupled ocean-atmosphere GCM experiments together with the results from the statistical downscaling. Relatively great emphasis is put on the results from the GCM model from the Geophysical Fluid Dynamics Laboratory (GFDL) because the large scale pressure distribution in this model is more realistic than for the other models.

The scenario specifies an annual warming rate of 0.3° C (0.35° C in winter and 0.25° C in summer) for the western part of the area, increasing to 0.45° C (0.6° C in winter and 0.3° C in summer) in Finland, northern Norway and Sweden. A sinusoidal variation between the summer and winter values is assumed.

The scenario for precipitation changes is more problematic than the temperature scenario. The expert group specified precipitation changes as approximately 3-6% per degree of warming, using the lower part of the range in the continental part of the area and the higher values along the western coast of Norway where precipitation is primarily controlled by orography. The predicted precipitation changes are larger in winter than in summer.

Natural climate variability in the North Atlantic region is of a similar magnitude as the warming predicted by coupled ocean-atmosphere GCMs for this region in the next decades. The complex coupling between ocean circulation in the North Atlantic ocean and possible CO_2 induced climate warming will make it very difficult to differentiate human influence on the climate system from natural climate variability in this region for the next 20-30 years.

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