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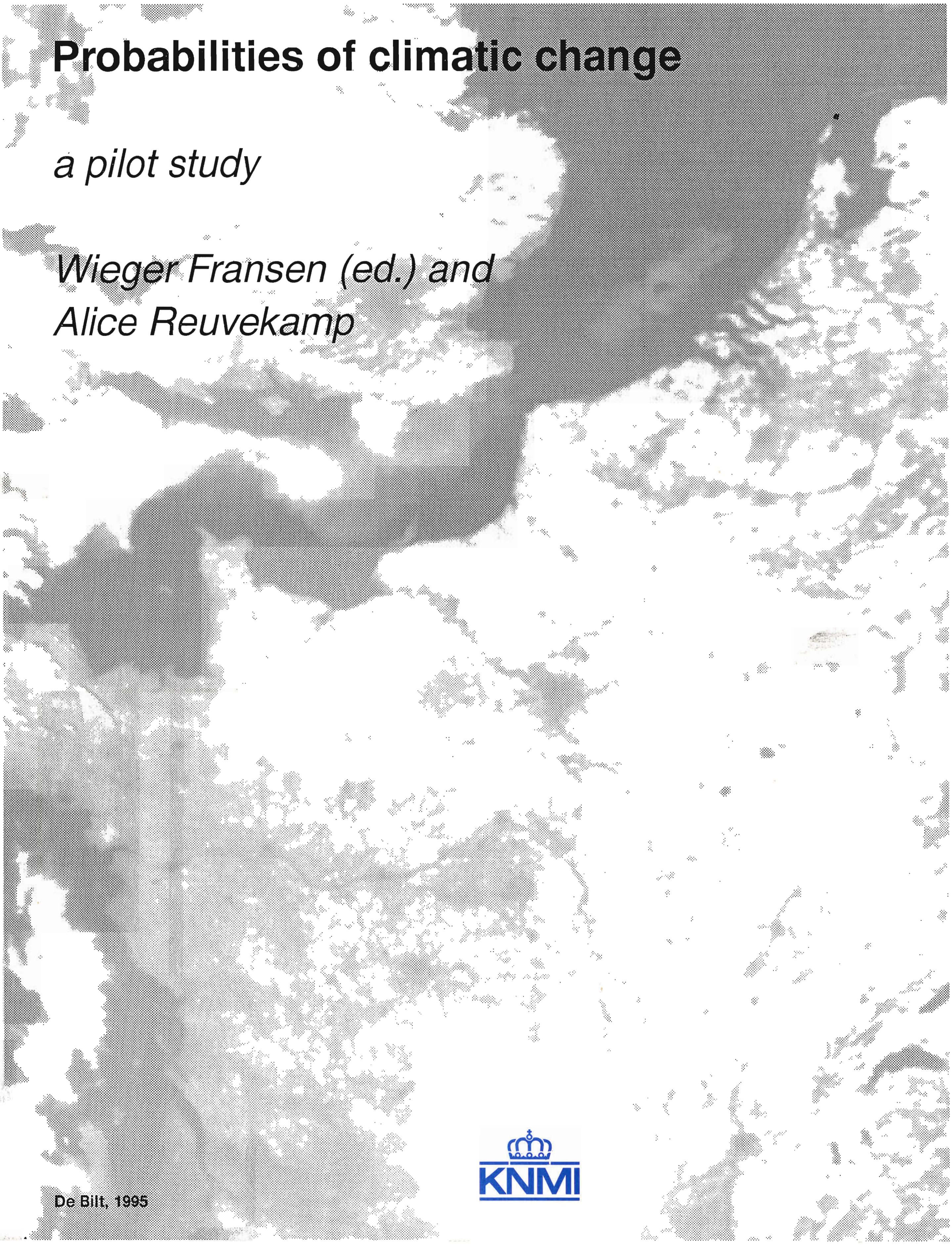

Probabilities of climatic change

a pilot study

Wieger Fransen (ed.) and
Alice Reuvekamp

KNMI

De Bilt, 1995

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PO Box 201
3730 AE De Bilt
the Netherlands
Telephone 030-206 911
Telefax 030-210 407

(after 10-10-'95
tel. +31(0)30-22 06 911
fax +31(0)30-22 10 407)

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Introduction to some important concepts

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- EXECUTIVE SUMMARY-

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Abstract

A methodology aimed at supplying quantitative probabilistic statements on climatic change, which reflect the current state-of-the-art in the field of the atmospheric sciences including its associated uncertainties, is developed and tested. It is concluded that the methodology can be used as a tool to facilitate the dialogue between scientists and policymakers.
The methodology has been explicitly worked-out to provide probabilistic temperature forecasts. It is shown that the resulting method provides results suitable for use in a risk approach.

Results of the problem analysis

A risk approach aims at quantifying uncertain events leading to adverse effects. It is found that risk approaches which have been developed within other disciplines could not be used straightforwardly in the context of climatic change. For this, specification is needed; first about the types of risks which should be addressed, then about how these risks change when the temporal and spatial scope is changed, and finally about the balance between losses and benefits.

Information about the climatic change is often presented as the change in global mean temperature after full adaptation of climatic system to a forcing associated with doubling of the carbon dioxide concentration in the atmosphere. This condensed form of information may lead to an oversimplified perception about the risks involved. Several misconceptions are identified. First, results referring to a full adaptation of the climate to enhanced CO2 apply to a situation which will not occur in the foreseeable future as opposed to time-dependent results. Second, the climatic change will consist of temperature changes, but also of changes in climatic variables which are more risk-prone, like precipitation. Third, the climatic change will lead to changes in means as well as to changes in higher statistical momenta, affecting the distribution of extremes and accumulated events. Fourth, the climatic change and, thus, its risks will not be distributed uniformly over the globe.

The problem analysis leads to the following recommendations. First, considering the high spatial variability of climates and of biogenic and anthropogenic systems, a risk analysis of climatic change can only be established for the regional or the local scale. Second, as different models predict different climatic changes for a well-defined area, a risk analysis based on climate-change scenarios is recommended. Third, an assessment of the effects of simultaneous changes in several climatic variables will lead to a more comprehensive assessment of the risks involved. Fourth, climatic changes due to land-use changes should be assessed to put climatic change due to greenhouse increases and its associated risks in perspective.

These results stress the need for co-operation between climatologists, impact scientists and policymakers.

Conceptual constraints

Fundamental knowledge about the predictability of weather and climate indicates that the issue of climatic change can only be addressed when the exact chronological order of the changes is disregarded. It indicates also that new or unconventional experiments lead to a better, and possibly unexpected, understanding of what may happen under conditions of enhanced greenhouse forcing.

Knowledge about the foundations of probabilistic reasoning is rewarding. First, it leads to sympathy for those who state that realistic probabilistic models about the future cannot be developed. Second, all probabilistic statements referring to real-life situations concern 'what-if' situations; they are thus conditional. Third, the concept of probability can be given several meanings resulting in different probabilistic answers to one specific question even when the same evaluative basis is used. Fourth, use of different sources of information leads to different probabilistic statements. Fifth, as probabilistic statements with different levels of accuracy can be produced, the required accuracy is to be pre-specified.

The incorporation of uncertainty into probability calculations on climatic extremes provides guide-lines about policies of apparent overprotection and of adaptation.

Probabilistic methods identified

Quantitative probabilistic results on future climatic change have in the past been obtained by three methodologies. First, frequentistic probabilities result after statistical analysis of meteorological time-series from real-time measurements and from simulations with large climate models. Second, expert opinion should be considered as additive to time-series analysis; subjective probabilities result when a person is willing to make probabilistic estimates or to make bets. Third, a survey of expert opinion can lead to probabilistic results by categorizing options for response and by weighing opinions according to expertise. However, a methodology which accounts for all sources of information and uncertainty -already identified and yet to be identified- could not be found. Such an integrating methodology is developed here.

The methodology developed can be worked-out for any climatic variable, on any geographical scale, and for any time horizon. Output from coupled climate models is recommended as a starting-point, because it is based on an elaborate physical description of the climatic system and because it has a realistic timing and comparatively high spatial resolution. After determination of a probability distribution which is most suitable for the climatic variable under consideration, five categories of information are quantitatively integrated. 'Modelled wisdom' covers the knowledge which is already accounted for in the models. 'Added wisdom' accounts for knowledge which exists and which is already (partly) quantified in some way, but which is not yet accounted for by the coupled models. It is then acknowledged that there remain processes influencing (future) climate which are not yet known. They reduce the certainty about the global temperature increase in a two times CO_2 climate ('global ignorance'). In addition, when going from the global to the zonal scale and from the zonal to the regional scale, the amount of physical processes which remain unresolved increases. The uncertainty introduced by these transitions is quantitatively accounted for under the headings 'zonal ignorance' and 'regional ignorance', respectively. In combination with the adapted probability distribution, these five parameters allow the calculation of the probability of exceedance for a specific threshold of a climatic variable.

The methodology is generally applicable; it is at the same time transparent and simple. As such it may facilitate the dialogue between scientists and policymakers. The methodology allows easy adaptation to incorporate additional knowledge, new insights and new numbers; it can be recalculated at any point in future time. As the balance between knowledge and ignorance is shifting continuously, the method applied can be considered as time-dependent; it will always give a new result. The methodology enables the expression of contemporary knowledge in terms of probabilities, whatever the degree of physical uncertainty or of ignorance. Consequently, it will always provide a quantitative result. It is up to the user to decide whether this result has some value within the context of his or her problem.

Case study for temperature

The methodology proposed is worked-out explicitly for temperature. Quantitative probabilistic predictions for the temperature in 2060, i.e. at the time of CO2 doubling with respect to 1990, are obtained for the global situation, for a latitudinal band centred at 53N ('zonal scale'), and for Western Europe ('regional scale'). It is assumed that the set of temperature predictions is normally distributed around a mean value. Uncertainty introduced by natural variability, anthropogenic aerosols, sensitivity on initial conditions, the cold-start phenomenon, emission rates, and cloud modelling, are quantified under 'added wisdom'. Intrinsic ignorance and its increase when going from larger to smaller geographical scales have been subjectively and quantitatively equated with the sum of the standard deviations which have been deterministically applied to the first two categories. Results obtained are compared with results from palaeo-climatic studies; they agree well. The results are as follows: temperatures in 2060 will have changed by between -1.0 and +4.6 °C (globe) and by between -2.3 and +6.5 °C (Europe) with a probability of 95% compared to the situation in 1990. Vice versa, there is a probability of 2.5% that Europe will have warmed by more than 6.5 °C in 2060 compared to 1990. Schematically this gives:

Category of uncertainty	*Correction* and σ in °C for the global scale	*Correction* and σ in °C for the zonal scale	*Correction* and σ in °C for the regional scale
Modelled wisdom	+*1.9* ±0.5	+*2.8* ±0.8	+*2.2* ±0.8
Added wisdom	*-0.1* ±0.8	*-0.1* ±1.1	*-0.1* ±1.1
Global ignorance	±1.0	±1.0	±1.0
Zonal ignorance	-	±1.0	±1.0
Regional ignorance	-	-	±1.0
Final sample result	+*1.8* ±1.4	+*2.7* ±1.9	+*2.1* ±2.2

Table I. Corrections and sample standard deviations σ for different categories of uncertainty are given. They determine the predicted temperature changes for 2060 with respect to 1990 including the limits between which the temperature change will be with a probability of 68%. Twice this standard deviation represents the interval which encompasses the temperature change in 2060 compared to 1990 with 95% probability.

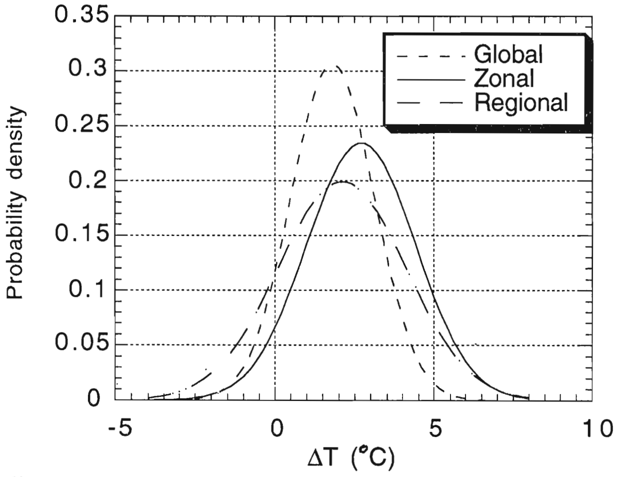

Figure I. Normal distribution for the temperature increase in 2060 with respect to 1990 for the global, the zonal, i.e. a zonal band centred at 53 degrees Northern latitude, and the regional scale, i.e. in Western Europe including the Netherlands.

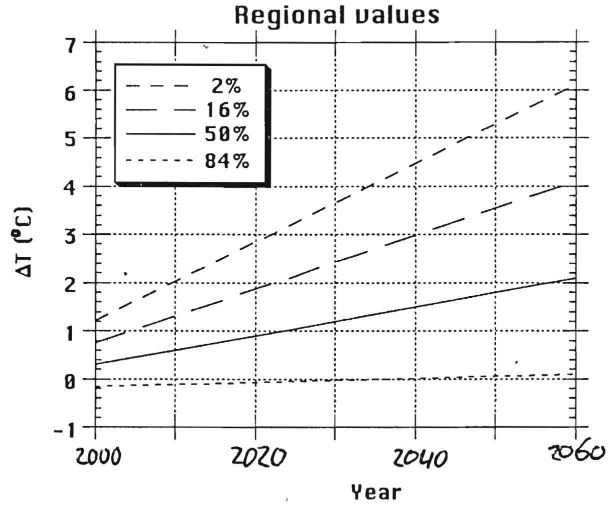

Figure II. Probabilities of exceedance (see box) of a temperature change in Western Europe, which includes the Netherlands, of at least ΔT degrees Celsius (vertical axis) as a function of time (horizontal axis). The lines follow straightforwardly from Figure I.

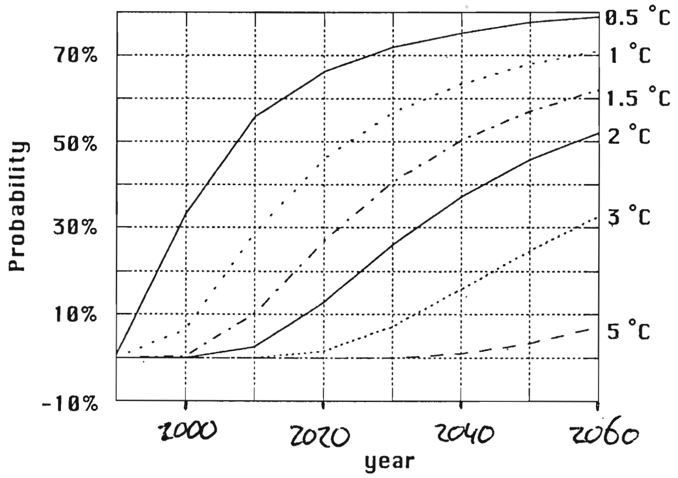

Figure III. The probability that the Western-European warming exceeds pre-defined thresholds.

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PREFACE

Atmospheric scientists agree that the Earth will warm if the atmospheric concentration of greenhouse gases will continue to increase. It is generally accepted that an increase in radiative forcing equivalent with forcing from a doubling of CO_2 will ultimately result in a global warming of between 1.5 and 4.5 °C, with a best estimate of 2.5 °C. This increase in forcing will occur in the first half of the twentyfirst century. The concomitant temperature increase will lag decennia to centuries due to, in particular, the large heating capacity of the oceans.

The range of warming rates given is, with current knowledge, considered the most probable. At the same time it is acknowledged that the anticipated warming might be smaller or larger. This has as consequence that policymakers meet large difficulties in formulating an unequivocal policy aimed at either adapting to or mitigating the impacts of climatic change. Indeed, the impact on society of a climatic change and, thus, of measures to be taken will be far larger for an anticipated global warming of 5 °C than for a warming of 0.5 °C. It is obvious that with such spread in the predictions it is hardly possible to operationalize a 'what-if' concept -normally a sound basis for policy formulation- and, accordingly, to take appropriate measures; there are just too many ifs and, consequently, too many whats.
On the other hand, if climatologists manage to associate a probability with certain scenarios of climatic change, this situation might change. If probabilistic statements with respect to climate change can be produced these could in principle be used as input for impact studies. If so, a risk-assessment is effectively established. This can be used as a tool by policymakers for decision-making, to some extent comparable to the way risk-assessments aimed at dealing with nuclear energy were used in recent history.

This report, which has been commissioned by the Air and Energy Directorate of the Directorate-General for Environmnetal Protection of the Dutch Ministry for the Environment, aims at providing an inventory of methods which can be used to produce quantitative probabilistic information about future climatic change. In addition to the methods found it presents an alternative method. This method is used in this report to provide probabilistic information about the climate in about the middle of next century on three spatial scales. As one of these scales concerns Western Europe and, thus, The Netherlands the information can be used by Dutch policymakers for the first step of a risk-assessment on the issue of climatic change.
The study has been carried out in the period 1 September 1994 till 1 May 1995 at the Royal Netherlands Meteorological Institute KNMI.

GENERAL INTRODUCTION

Aim of the underlying study

Is it possible to present information with respect to the predicted climatic change for The Netherlands and elsewhere for the year 2050, which is due to the substantial current and on-going rise in greenhouse gas concentrations in the Earth's atmosphere, in a probabilistic form? That is the question which this study tries to answer. The answer should be the first step on the road to the long-term objective, i.e. a quantitative assessment of the risks and opportunities of an anthropogenically induced change in the climate.

Set-up of the study

Before the above question will be dealt with in detail some background information is presented. This information concerns an analysis of the problem as well as an introduction to some concepts of which a basic understanding is needed in order to judge the value of the probabilistic statements provided in this report.

Then an attempt is made to provide an answer on the question posed. This has first been tried by the easiest possible way: see if other people have already tried to do so in an accountable way. If so, the answer is yes when they succeeded. The idea was to impose two constraints on the information gathered from this search and to be used in this study. The first one is explicitly mentioned in the beginning of this alinea: the method used to produce the kind of information sought for should be accountable. This is for the current study defined as follows: a method leading to probabilistic statements is considered accountable:

a) if the results of an intrinsically objective method, e.g. the use of a statistical or mathematical model, have been accepted for publication in a archieval journal of which the contents have been subject to the process of peer-review, or
b) if the results of an intrinsically subjective method have been established by an independent institute in a way which is described accurately and can be simply reproduced, or
c) if subjective statements have been done by acknowledged experts in the field in a hearing before a panel with a large authority, e.g. a congressional hearing.

list 0-1

The second constraint should have been that probabilistic information about future climate should not be based on statements on future climate which had no probability attached. For instance, some studies have been found which present probabilistic information with respect to future regional rain patterns for a regional warming of, say, 1 °C, without discussing the probability of the latter event. However, results of these studies -so-called sensitivity studies- will be presented because they may present useful information for people dealing with scenarios of possible future regional climates. In addition, the examples will make clear which opportunities for probabilistic regional climate predictions are latently present if reliable probabilistic information on warming -in this example on a regional scale- due to greenhouse gas increases will prove possible. A last reason to present the results from sensitivity studies is that relatively few results were available for this study anyway. The second contraint had as result that the study focusses on probabilistic results with respect to global mean temperatures in a two times CO_2 climate, changes in other climatic variables being derivatives of global mean temperature change.

In addition an alternative approach has been followed to produce probabilistic statements on the future climate. This has been done both to see whether already existing results are confirmed and to correct for processes which acknowledgely have a direct or indirect influence on the future climate but which have not been accounted for in the methods identified.

This approach is based on the idea that output from the state-of-the-art climate models, i.e. the so-called coupled General Circulation Models, is the most reliable source of information concerning the future climate, while it acknowledges at the same time that many important processes identified are not yet accounted for by these models. The influence of these processes has been quantified and the prediction of the models for the future climate have been adapted accordingly.
Thus, in addition to the outcomes of the models considered three kinds of additional processes have been taken into account in the final probabilistic prediction for the climate in about the middle of next century. First of all, processes which may influence the model outcomes have been identified which are known and which have already been quantified to some extent. These are both processes which can be associated with the climatic system, like the influence of anthropogenic aerosols on the radiative balance, and processes which should be considered as an artefact of the climate modelling process. An example from the last category is the cold-start phenomenon which addresses the fact that climate change simulations start from a relatively unperturbed situation while it can be said that in reality the climatic system is being perturbed since anthropogenic emissions of greenhouse gases have become significant compared to the natural emissions, i.e. since about the middle of the twentieth century.
Secondly, the model output has been corrected for the fact that physical processes which are resolved on larger spatial scales -for instance many processes like average cloudiness and global mean precipitation are often tuned to match the available statistics on these processes- are not correctly resolved on smaller spatial scales. This adds uncertainty, or bandwith, to the results already obtained. It has been tried to subjectively quantify the uncertainty associated with this transition from larger to smaller spatial scales.
Thirdly, it can be defended that independent from the efforts made to address all the existing uncertainties one can confidently say that large uncertainties have been overlooked. These uncertainties can be associated with the evolution of scientific knowledge (e.g. it may turn out that climate may change much more rapidly than previously thought), with the evolution of technology (e.g. some people are waiting for an 'Archimedes of CO2 Storage' to exclaim 'Eureka'), with the fact that nations have not always been so polite to one another in the recent past (e.g. think about the effect a third World War may have on the climate), and with the occurrence of so-called 'Acts of God' which can by definition not be predicted till any extent whatsoever (e.g. an epidemic which puts AIDS into the shade). This kind of uncertainty has, again, been quantified subjectively.

A discussion and conclusion will end this report. It will be tried to indicate which kind of probabilistic statements are most suited for use in a strategy by policymakers aimed at getting support for measures to be taken in order to either adapt to or mitigate the climatic change due to the anthropogenically induced enhancement of the natural Greenhouse Effect.

Information used

For the problem analysis (Chapter 1) ideas from the authors were used as basis. These have acknowledgely been largely influenced through discussions with other scientists from KNMI. In addition, many ideas were obtained during the international conference on 'Climate Change Research' which was held in Maastricht from December the sixth to December the ninth, 1994. A so-called interactive poster was presented by the authors of this report which identified some key questions which should be addressed first if the objective is to produce probabilistic statements on climatic change aimed at underinning a risk assessment on this issue. The poster invited participants of the conference to react on the key questions identified, which they did.

The chapter about the requirements for probabilistic statements (Chapter 2) has been based on own ideas as far as the context of the predicted climatic change are concerned. Again discussions at KNMI and during the above mentioned conference have had a large impact on the presentation of the information.

The introduction to some important concepts (Chapter 3) was largely based on work by other scientists. Section 3.1 on the predictability of weather and climate has been primarily based on work by Edward Lorenz (Lorenz 75, 82 and 85, in particular), one of the first meteorologists to address the issue of predictability within the atmospheric sciences and certainly the most renowned. Section 3.2 about the foundations of probabilitic reasoning has been largely based on articles which can be found in the Encyclopedia of statistical sciences (Kotz et al. 83). The section which addresses the risk concept (Section 3.3) is adapted from a publication of the Swiss Reinsurance Company (Swiss Re 94).

For the inventory of probabilistic results on climatic change (Chapters 4 and 5) which had yet been published, a literature search has been carried out. Not many appropriate publications could be found. So, in addition, a request for information has been distributed. First among scientists within KNMI and later among scientists which are connected to the Dutch national research programme on global air pollution and climate change NRP as well as to scientific journalists and people from environmental institutions. The last category was approached because there is good reason to believe that people belonging to this category are well informed about developments in this field of research as it might be easily accepted that they are eager to obtain the information asked for. In the request was asked for any study in which quantitative probabilistic information with respect to climatic change was given.
This information includes results in terms of confidence limits, hypothesis rejection at well defined levels of confidence, probabilities, bandwidths, et cetera. About 50 requests were distributed within the department of research of KNMI. Five responded, of which only one could be considered accountable according to the above mentioned criteria. Again 50 requests were distributed among scientist associated to NRP as well as among journalists and people from the environmental movement. To date about twenty reactions have been received. However, only few people did mention studies which belonged to the category of publications sought for. From those, two have been considered accountable and are presented in this study. A similar request was sent later to the authors of the relevant studies from abroad which had been brought together so far. Of this small group of eight research groups three reactions have been received. Altogether, about twenty publications from six research groups were considered suitable for qualitative analysis.

Chapter 6 presents calculations for the climate in about 2060 for three geographical scales based on information which can be found in the scientific literature. Originally the idea was to organize two discussion rounds within KNMI which would help in quantifying uncertainty due to modelling of cloud processes and of ocean circulation. Lack of time resulted in the fact that only one discussion round, the one about cloud processes, was actually organized. The accompanying information form can be found in the appendices.
Additional uncertainties, i.e. those due to unknown, but plausible surprises and to the transition from larger to smaller geographical scales, have been subjectively quantified.

The study ends with a discussion and conclusion.

CHAPTER 1

Assessing the risks and opportunities of a change in the climate; analysis of the problem from the perspective of a climatologist

Chapter 1 explains that:

1) a risk approach of climatic change may be a solid base for policy formulation,
2) before a study on the feasibility of such a risk approach is initiated, policymakers should make clear what the setting or context is against which the risks should be assessed, and
3) the quantitative information on the predicted climatic change used most often is not suited for use in a risk approach.

list 1-1

1.1 Introduction

In Section 1.1 it is argued that:

1) when a risk for society is identified several steps in the process of decision making should be addressed leading politicians to undertake appropriate action,
2) climate is changing due to anthropogenic activities is considered reality among both atmospheric scientists and policymakers involved,
3) future climate is uncertain by nature, and
4) this requires in the context of assessing the impacts of a climatic change an approach which deals with uncertainty effectively.

list 1-2

When a potential dangerous occurrence for society is identified, several steps should be followed before the action required to render this occurrence harmless can be undertaken in an accountable way. Theoretically, and after identification of the threat, these are:

1) **verification**
   People who are in the position to commission appropriate action by society, usually policymakers, should ascertain themselves and, as such, society that the (predicted) dangerous occurrence is real, i.e., that it may in fact happen or that it is already happening.
2) **impact assessment**
   If the policymakers are convinced or agree that the (predicted) danger is real, the question what its consequences are should be answered. This is usually done by scientists.
3) **weigh of positive and negative effects**
   If it is made clear what the impacts of the dangerous occurrence will be, the predicted situation after the dangerous occurrence should be compared with the then current situation to consider the net adverse effects of the occurrence. This is usually done by scientists.
4) **estimate of in- and external costs of change in behaviour**
   If the net effect is indeed adverse, policymakers will ask for an assessment of the efforts needed to render the danger harmless or to mitigate or avoid the impacts. This is again a job for scientists.
5) **political decision**
   Finally, policymakers will weigh the costs of the change in behaviour against the costs of addressing the impacts. Based on this second weigh they will undertake action.

list 1-3

In reality, the complexity of assessing causes and effects of many predicted dangers will not allow a step by step completion of the approach proposed. For example, after the verification step the answer on the question whether a danger is real can be 'may be' or 'depends' instead of 'yes' or 'no'. This will have an impact on the completion of the remaining steps. Furthermore, the steps are not usually considered subsequently but mostly in a more or less coincidental way and they are often followed more than once and continuously in time. The five steps can be considered as a sound model for the process of decision making in sight of a potential threat though.

Now, let us consider the risks and opportunities of a change in the climate due to anthropogenic activity. It can be easily defended that the verification step has been passed by now. The consensus among both scientists and policymakers is that the climate will change due to anthropogenic interference. So, the second step, 'impact assessment', should be addressed. But already at this point the difficulties start, mainly because of uncertainties associated with the sign and magnitude of the change in the geographical and temporal distribution of many variables determining climate. This leads to the conclusion that there may be many consequences, severe and less severe. Indeed, it cannot be said in advance that the positive consequences, i.e. opportunities, may be less than the negative consequences, i.e. risks.

From a scientific viewpoint, the uncertainties associated with the issue of climatic change make the issue even more interesting. Policymakers, however, require univocal statements. In this perspective can it be defended that until recently professionals working in the field of climate policy followed the wrong strategy by pursuing statements with respect to the predicted climatic change with no associated uncertainty. The climatic system is complex by nature and the perturbation of complex systems does not usually result in a distinct and easily distinguishable change but rather in a set of more or less plausible states for a specific place and time. From both theoretical considerations and observations of past climates, there is good reason to believe that these plausible states may represent significantly different but equally likely climates, especially when the focus is on smaller geographical scales and longer time scales. Because of this, univocal statements may not be expected.

Policymakers have in recent history shown how to deal with uncertainty adequately. At least, that is, if they are enabled to change the usual paradigm of policymaking, i.e. policy based on (accepted) certainties, as this does not provide a solid base for the implementation of measures aimed at mitigating, or adaptation to, uncertain changes. Moreover, the general public on which policymakers rely will in general not support decisions concerning uncertain developments if they are put in terms of uncertainty and if they result in stringent measures. This is often due to its perception of uncertainty, which basically comes down to 'it may well not be so'. So, information on the future climate should be presented in such a way that a different paradigm to the issue of climatic change is presented to the policymakers; a paradigm which deals with the uncertain nature of climatic change in a way which provides a tool for assessing the impacts. This will lead to a solid foundation for both policy formulation and public support. This paradigm could be a probabilistic approach of climatic change. This approach has as additional advantage that its results, if quantitative, may be used for a risk assessment of climatic change.

1.2 The risk approach

It follows from this section, which rather deals with the process of public-policy decision making, that a risk assessment of climatic change can only be used successfully by decision makers if it is made clear to and by them in advance:

1) that the opportunities of a climatic change have also been taken into account in the assessment,
2) whose risks have been assessed, and
3) what category of risks has been assessed.

list 1-4

In this study an attempt is made to allow the use of the risk approach for the issue of global warming. This is done by providing quantitative probabilistic statements on climatic change. The perspective is a climatological one.

Events occurring naturally, be it with or without initiation by man, have often large associated uncertainty with respect to timing and impact. This is largely due to the uncontrollable nature of such events. However, when there is uncertainty whether a certain occurrence will happen it does not mean that nothing can be said with any certainty. A well known method to present some quantitative information on uncertain events is the probabilistic approach.
In the case of a very simple system which describes the occurrence of either event A or event B, the probabilistic approach ideally leads to the statement that it is for an arbitrary percentage X certain that option A will occur and that it is for arbitrary percentage Y certain that option B will occur. The percentages X and Y should add to 100%.
At the other end of the spectrum one will find complex systems: many probable realisations which are each not very well defined, i.e. they have an associated uncertainty or bandwidth, accompagnied by the near-certainty that some probable realisations have been overlooked. For such complex systems, a probabilistic approach may finally result in the conclusion that a specific event, e.g. a change in the climate, may happen in different disguishes which each have an associated probability. The probabilities, which follow from theoretical considerations and observations in the past, when added do not necessarily lead to a 100% coverage of all probabilities of future states; surprises can never be ruled out. They may, however, be accounted for till an unknown extent by, for example, increasing the bandwidth which covers the predicted future realisations.

Changes in variables which are not considered as having an intrinsic value by their existence or occurrence alone, cannot be considered as being good or bad in advance. However, it should be acknowledged that this is just the kind of information which is needed by, for example, politicians. Indeed, how can politicians undertake appropriate action if they have no idea about how prosperous or damaging a well-defined climatic change will be? This judgement can only be made when wanted or unwanted impacts, for example for society, are associated with changes in the variables determining climate. If so and if probabilities had already been associated with the climatic changes, a probabilistic approach is effectively turned into a so-called risk approach or risk assessment. Risk approaches have been known for quite a long time. Note their use for assessing the risks of a new nuclear energy plant for its environment for instance.
A risk approach can be considered as the opposite of an opportunity approach. The usual way of presenting probabilities in lotteries can be called an opportunity approach. A risk approach points at the probability that an event occurs that is nòt desirable, an opportunity approach points at the probability that an event occurs that is desirable. If both probabilities are added the remainder of the probable events belong to the category 'desirable nor undesirable'.

It should be stressed that climatic change will also have beneficial effects. Indeed, as risk assessments on the global warming issue have not yet been done, it cannot be said in advance that the risks will be smaller or larger than the opportunities. This is a point that has been and still is overlooked just too easily. Think for instance how prosperous more rainfall could be for large areas in the Northern parts of the CIS, where at present no corn can be grown.

For the successful completion of the risk approach, input is needed from the end users of probabilistic statements on global warming: decision makers, policymakers and politicians. Policymakers, for instance, should make clear whose risks and opportunities should be studied. From an anthropogenic point of view can be defended that the answer on this question is dependent on the people who, or institutions which, decide over, or are in power in, a specific area: the decisive bodies. Consequently, the following hierarchy is proposed:

1) Bodies operating intercontinentally (e.g. UN, OESO, and OPEC),
2) Bodies operating continentally or transboundary (e.g. EU, USA, and BENELUX),
3) Bodies operating nationally (e.g. nations and states),
4) Bodies operating locally (e.g. cities, towns, and municipalities),
5) Individuals, families, households, offices, shops, communities, et cetera.

list 1-5

Ideally, the bodies one to four should comprise of politicians only. The politicians in turn should ideally represent the interest of institutions like NGO's, industries, trade associations, organisations, et cetera, in the way as promised to all individual voters before the elections. In reality one may often have the impression that in certain regions some institutions have more power than the politicians in charge.
Another point which should not be overlooked is that the climatic risks for a specific country may partly depent on the climatic risks of another country with which it has a physical, economical, or some other relationship.

The question what kind of risks are we talking about or what evaluative basis should be used to accomplish this risk assessment is, again, an important question as the answer may demarcate the geographical area, time-horizon and climatic variables that should be investigated. One may think of the following kinds of risks which may underly a risk assessment of climatic change:

1) Damage to, or loss of, ecosystems (leading to an increase of the 'natural debt'),
2) Direct economical loss (which may also be expressed by changes in discount rate),
3) Damage to the physical and mental health of people,
4) Political instability due to indirect socio-economic effects (climatic change may indirectly lead to migration of large groups of people. It may also lead to tension between neighbouring countries if, for example, the agricultural production increases in the first country and decreases in the second),
5) Food production (including agricultural production and fishery).

list 1-6

Due to the fact that the current study has been set up as an inventory study the above questions have not been addressed. Indeed, one of the purposes was just to identify key questions on which the risk assessment of climatic change should be based. They should be addressed, however, if it is decided to elaborate on the results of this study. For the risk approach, first of all probabilistic statements on the expected climatic change are needed. The underlying report aims at providing such results -in addition to the identification of the underlying key questions- both by exploring a simple, new method and by presenting results from studies by other institutes. If probabilistic results can be provided they should be used by scientists working in the field of impact assessment. If impact scientists manage to couple probabilistic statements on climatic change to impacts, a risk-assessment is effectively established.

1.3 The inadequacy of the information on the predicted climatic change usually provided

Contrary to what is often being thought:

1) the climatic change will not be distributed uniformly,
2) the climatic change will not consist of temperature changes only,
3) the statistical representation of the behaviour of a climatic variable with time for a specific area or place will not have the same characteristics in a two times CO_2 climate as in the current climate, and
4) the changes under CO_2 doubling will differ significantly from those obtained by performing equilibrium runs with climate models.

list 1-7

Predictions with respect to the expected climatic change used most often, by scientists as well as policymakers, concern changes in mean temperature on global scales for an equilibrium situation under CO_2 doubling. As result, most people know that the enhanced greenhouse effect will result in higher global temperatures. However, when addressing the risks of an enhanced Greenhouse Effect, these changes do not provide the information needed. In this section will be made clear why this is the case.

The climatic change will not be distributed uniformly. On the contrary, climate models as well as historical records present very dynamical patterns of climatic change with major contrasts between both magnitudes and signs of the predicted change for many climatic variables and for many regions. The smaller the geographical scales one is interested in, the larger the contrasts with the global mean situation generally are. Focussing on temperature alone, these patterns may imply that when the globe warms by, for instance, 2 °C, this may be constituted of a warming of, say, between 0 and 4 °C in the largest part of the world with regional extremes of, say, an 8 °C warming in many places and a cooling of, say, 1 °C in some places.
Moreover, climate models, while delivering mutually consistent results with respect to global-scale changes, all present slightly different spatial distributions regarding a global warming under CO_2 doubling. In addition, both models and historical records indicate that within each spatial pattern areas exist where the predicted climate shows a larger bandwith, i.e. more possible realisations, than in other areas. For example, one study presented results from four different runs with the same model from slightly, but equally likely different initial conditions. The standard deviation for the temperature distribution under a two times CO_2 climate which was calculated for the different areas had a spread of between a maximum of +/- 0.1 °C for large parts of the oceans in the tropics and a maximum of +/- 5 °C for large parts of the Arctic and for the Weddell sea near the Antarctic. These examples indicate that the global mean temperature gives only very limited information about what will happen in reality.
If theoretical considerations should be accounted for also, one may allow for a climatic change being the result of an average global temperature remaining constant while some regions exhibit a two degree warming and others exhibit a two degree cooling. This will then likely be accompagnied by changes in other climatic variables, e.g. precipitation and cloud coverage.

The climatic change will not consist of temperature changes only. It is yet unclear whether the largest risks (and opportunities for that matter) for society and nature concern changes in temperature. Indeed, among scientists working on the impact side of climatic change it is currently felt that differences in rain patterns may pose larger threats to society and nature than temperature changes.

Another reason why the focus on temperature changes may not result in statements which will lead to a accurate assessment of the risks is the fact that on theoretical grounds one cannot yet rule out a climatic change which does not result in significant temperature changes but in changes in other climatic variables, e.g. cloud coverage.

The climatic change will not lead to statistical distributions of values for specific climatic variables of which the means are different but which are otherwise comparable with current distributions. Currently, model predictions with respect to the expected climatic change cited concern most of the time changes in mean values. However, this general idea that average values for a specific variable, e.g. temperature, change while the form of the associated distribution remains the same will probably not become reality. It may well be so that prevailing patterns of the large-scale circulation will change, leading to changes in existing climatological relationships, e.g. between temperature and precipitation for a certain place on Earth. In addition, days with several extreme climatic characteristics, e.g. a combination of strong winds and heavy rainfall, may occur disproportionately more often under CO2 doubling. Obviously, both kinds of climatic changes may result in higher risks for society and nature.
But even without this kind of information may it be anticipated that society will become more interested in changes in the yearly occurrences of, for instance, freezing-days or tropical days than in changes in mean temperature. The same can be said about changes in run events with respect to precipitation., as these events are of eminent importance to farmers.

The climatic change will differ from the changes as obtained by performing equilibrium runs with GCMs. Model predictions with respect to the expected climatic change concern most of the time changes for an equilibrium situation under a doubling of CO2 or equivalent. When the aim is to establish a risk-assessment these results are not applicable. This is because they describe a situation which will very likely never be reached, i.e. equilibrium will only be reached when forcing conditions remain relatively constant over long periods of time and this will not happen in the foreseeable future, and because these results have no associated timing, i.e. results from equilibrium runs can only be seen as theoretical results in the sense that they describe a final situation of which cannot be said when, if ever, it will occur. Note that both features, i.e. whether or not an equilibrium situation will be achieved and the fact that no timing can be associated with the model predictions, are strongly interdependent.
The above text is effectively a plea for the use of results from time-dependent runs with coupled models. These models calculate the climatic change which accompagnies the gradual increase in CO2 concentration for each time step, i.e. 30 minutes to a few hours. Some significant differences in output result can be observed when these coupled models are compared to non-coupled or equilibrium models. For instance,the global distribution of temperature changes is different from those obtained by equilibrium models. In addition, because the thermal inertia of the climatic system is accounted for by a coupling with the deep-ocean circulation, time-dependent runs with coupled models result in significantly lower values for the temperature achieved at the time of CO2 doubling than comparable equilibrium runs; temperatures achieved at the time of CO2 doubling are about 60% of their equilibrium values.

CHAPTER 2

What kind of probabilistic statements are required?

In Chapter 2 is made clear that:

1) probabilistic information on future climatic change can be obtained if some well defined needs are met,
2) if climate change is put in the context of a risk assessment the concept of climate may need a different interpretation than hitherto usual, and
3) a closer look at the concept of 'change' may lead to a clearer picture about what kind of probabilistic statements are needed.

list 2-1

2.1 Introduction

Probabilistic statements on climatic change aimed at underpinning a risk assessment are only feasible when:

1) they apply to a region which experiences just one climate or areas within that region,
2) all model realisations which refer to a climate under CO2 doubling for a specific region are categorized in accordance with similarities in changes in one or more climatic variables,
3) impact scientists co-operate with climatologist in order to find out what changes in statistics of which climatic variables should be studied, and
4) results with realistic timing and high spatial resolution are used.

list 2-2

In Section 1.3 it has been argued that the regional climatic effects due to CO2 doubling as calculated with climate models are very diverse with respect to sign, magnitude, distribution, timing and variable, e.g. temperature or precipitation. This information was used as basis for the statement that the quantitative information on the expected climatic change presented usually does not tell us anything about what in reality will happen and is, thus, not suited for use in a risk assessment.

To start with the most important observation from the preceding section: in the real world there is no such thing as a global climate; it only exists in man's mind. Thus, risk analyses cannot be based on probabilistic statements with respect to the global-average situation. Extending this line of reasoning leads to the conclusion that univocal climatic changes can only apply to regions which just have one and the same climate or to areas within those regions. How large such a 'climate region' is, is largely dependent on prevailing circulation types. This definition may in the context of risk assessment have as additional advantage that the prevailing weather types in a region, as determined by the prevailing circulation, will be strongly related to the type of vegetation and, thus, the ecosystems in that region.

Yet another reason to disregard information on globally averaged climatic changes is the fact that models calculate for many regions several plausible climates under two times CO2. If the idea is to couple probabilities of occurrence to possible future climates, then it is probably wise to categorize the climates calculated. This may be possible if some of the climatic states calculated show significant similarities with respect to specific climatic variables, individually or combined. Then, probabilities should be associated with each category. Consequently, a distinct climatic state which is represented by one or more model realisations may then be considered as one possible realisation of future climate, i.e. as a climate scenario.

This brings us to the second and third issue which concern the emphasis on changes in temperature and in mean values. At this point, expertise from the side of impact scientists is needed. They should co-operate with climatologists in order to find out which climatic variables are most appropriate to study in the context of a risk assessment of the climatic changes under CO2 doubling. Which statistical features of these variables should be studied, e.g. occurrence of extremes or run events, should also be decided in consultation. It may be anticipated that these choices are dependent on whose risks and on the kinds of risks that are being evaluated (see list on page). For instance, when the issue is to calculate direct economical loss or damage due to climatic change, the risk assessment should use a different methodology in which other climatic variables and statistical representations are emphasized then when damage to ecosystems is calculated.

In addition, economical and ecological damage or loss may also occur when the climate in another region to which the region under consideration is in some way coupled changes. For instance, the occurrence of flooding of the Rhine is also dependent on changes in precipitation patterns over the total basin of the Rhine. For economical loss the coupling may even be very loose. Imagine for instance that climatic changes in Brasil disrupt the growth of food for the Dutch cattle.

It should be pointed out also that different systems show different sensitivities. Anthropogenic activity may well be insensitive to a climatic change in the sense that irreversible damage may not easily occur. For example, if damage to, for example, infrastructure will occur more often due to enhanced occurrences of specified extremes this may just mean that we have to invest more money. Consequently, the infrastructure will be rebuilt with as plausible macro-economic side effect that the economy will grow. On the other hand, it is accepted that ecosystems may experience large irreversible losses, for instance in biodiversity, when the climate changes. This will not happen in an evenly distributed way, however, as some ecosystems are more sensitive to a certain climatic change than others. In other words, for a well defined absolute change in the climate some ecosystems may experience a larger loss or damage than others. A related point is that it may well be the case that a specific region may experience less damage from a 3 °C warming than half of that region may experience from a warming of 4 °C.
In general can be said that risks are largest in regions in which the climatic change will be relatively large and in which the ecosystems or societies or both are relatively sensitive to changes in the climate. This again stresses the importance of a 'climate-region' related approach.

The fourth point from Section 1.3 questioned whether climate models are able to present changes with a realistic timing. If coupled GCMs are used the answer should be yes, because these models are currently the only models which present climatic changes for each point in time in the future, provided that no higher time resolution than daily averages is required.
But when the objective is to deliver climatic information for a risk assessment, realistic timing of model results is not enough. Information should also be presented with high spatial resolution. Current state-of-the-art coupled-GCMs have spatial resolutions on the order of 2.5 degree latitude times 3.75 degree longitude, i.e. 250 km times 350 km. The spatial resolution desired, by impact scientist as well as decision makers, may be as small as 50 km x 50 km. This is the spatial resolution of current state-of-the-art weather models like the model from ECMWF.
Although spatial and temporal resolutions of GCMs are enhanced continuously, this mismatch in spatial scale and, to a much lesser extent, specificity in time between GCM output and surface data required by users having close links with society is not likely to improve significantly in the near future. Several reasons for this can be given. Any improvement in resolution requires additional modelling of finer-scale atmospheric processes and surface features that are responsible for regional climatic patterns. Both the enhancement of the resolution and the simulation of small-scale processes in a GCM will result in an increase in the volume of data generated. This will either tax the computers currently used for running these models or point at the need for buying even stronger computers. Both situations may be prohibitive in performing the required experiments. The 'all-in-one' solution of continually improving GCMs is not the only strategy for simulating future climate on smal spatial scales with high temporal resolution. 'Downscaling' the GCM output is another approach in order to realize detailed climate scenarios.
Two approaches, which should get more attention, are the use of transfer functions to translate large-area averages into point estimates, and the use of nested models to provide further refinement to coarse-scale GCM output.

2.2 What should be known about climate in the context of a risk assessment of climatic change?

If a risk-assessment of anthropogenically induced climatic change is the objective, emphasis on features of a specific climate should be given in accordance with:

1) the impact on society a change in a specific feature might have,
2) which changes in what statistical representation of this feature are of most concern, and
3) the area of interest with regard to the expected climatic change.

list 2-3

When discussing an arbitrary climate, usually only a few of all its characteristics are emphasized. Which are emphasized depends strongly on the context. If we go to a ski resort we are interested in the average amount of snow which usually falls at that place during a specific period; if we go to the beach we will be more interested in average temperature and cloudiness. These examples make clear that climate can be represented in several ways and for several areas. By using the term 'average' they make clear also that each representation used in common parlance is a statistical representation. This leads to the following general definition of climate: 'climate is a statistical representation of the characteristics of the weather during a well-defined period of time and for some well-defined place or area on Earth'.

Although one might get the impression, there is no clear distinction between weather and climate. For example, if the values for the daily mean temperature for one year are averaged the mean temperature for that year is obtained. This is no characteristic of the weather, especially if one knows that De Bilt experiences four periods each year which differ significantly in character regarding the weather, i.e. seasons. Neither does the value obtained tell a lot about the climate of De Bilt if one is aware of the fact that both the inter- and intra-annual variability of temperature is large and that the same often counts for other climatic variables.

2.2.1 Which characteristics of the weather should be represented?

The characteristics of weather which are generally monitored at meteorological stations consist of the following variables: atmospheric pressure, wind direction and speed, temperature, relative humidity, vapour pressure, global radiation, sunshine and cloudiness, amount and duration of precipitation, evaporation, and phenomena which, for several reasons, can only be observed visually, like rain, fog, snow, freezing precipitation, hail and thunder. These variables are continuously measured and they are recorded numerically for each hour or each day after either integration over the respective period of time (e.g. in the case of rain) or determination of extreme values in the respective period of time (e.g. in the case of temperature).

Each of the variables mentioned could, after some sort of statistical treatment, be used as an indicator of climate. However, when assessing the risks and opportunities of a change in the climate one should narrow the scope to those variables of which changes are in some way, directly or indirectly, of importance to policymakers. Four categories of such variables could be identified. Two of these comprised variables which were considered to be strongly related.

The four categories are:

1) Precipitation (intensity and surplus, i.e. precipitation minus evapotranspiration),
2) Temperature (extremes, averages, freezing days and 'tropical' days),
3) Cloud coverage and irradiance (of both short-wave and long-wave radiation),
4) Storms, tidal amplitude and sea-level.

list 2-4

It should be added that risks and opportunities of a climatic change may also be due to simultaneous changes in several variables. These changes, which do not necessarily all have to be of climatic origin, do not have to be significant by themselves. However, they may be when they occur in ensembles or, if they were already significant, their impact may be enhanced disproportionally if they occur in ensembles. This is called multi-stress when risks are addressed.

2.2.2 How should weather be statistically represented?

Climate has been defined above as 'a statistical representation of the characteristics of the weather during a well-defined period of time and for some well-defined place or area on Earth'. More loosely this turns into 'the characteristics of weather seen over longer periods'. However, depending on how weather information is statistically processed, one and the same climate could be presented in different forms. Many categories of statistical representation can be identified. Some important ones are:

1) Extreme values,
2) Averages,
3) Trends,
4) Variability,
5) Spatial and temporal correlation,
6) Run events,
7) Distribution,
8) Timing.

list 2-5

If meteorologists are interested in the characteristics of the climate for a specific place or area, yearly values are averaged over periods of at least ten years, but this is no rule of thumb. If a place experiences distinct seasons, seasonal values are averaged and presented alike. It is also common that information on extreme values accompanies the yearly averaged values.
Howvere, a risk assessment of climatic change may put different demands on the representation of climate. Dependent on the kind of risks one wants to investigate (see list 1-6 on page 14) one may decide that one statistical representation in particular may suit the risk assessment best. For instance, in daily life extremes in weather are important aspects of the climatic record. Hence, daily weather reports usually include the highest and lowest temperatures ever recorded at that date. Climatic summaries typically identify such extremes as the coldest, warmest, driest, wettest, snowiest, or cloudiest month or year on record. Farmers, on the other hand, are interested in knowing the long-term average rainfall during the growing season as well as the frequency of drought. In that case run events may be the climatic representation of interest. Electric utilities are interested in the hottest summers and coldest winters on record expressed in degree-days so that they might anticipate extremes in residential energy demands.

2.2.3 Should the concept of climate be restricted to a certain geographically defined area?

It can be observed that when people or the media discuss climatic change, global or hemispheric values are presented, if any. The same can be said of many scientific reports and of policymakers summaries of such reports, for instance of the IPCC. In general it can be said that 'the global climate' is an empty concept; there is no such thing as a global climate. This is made clear by the following example, which at the same time links the question of geographical scale and risks of climatic change. Four coupled models predict that the global temperature will have increased by between 1.3 and 2.3 °C at the time of CO_2 doubling. All four models show local heatings of up to 2.5 °C, one of up to 5 °C, one of up to 6 °C, and one of up to 7 °C. Two models also show regions which will *cool*, one of these even up to -6 °C. In other words, globally averaged climatic change does not capture the full dynamics of global climate change, neither does it give any information about the level of agreement between the different studies on regional temperature effects. Thus, risk analyses should not be based on probabilistic statements with respect to the global-average situation.

Extending the above line of reasoning leads to the conclusion that univocal climatic changes should, in the context of a risk assessment of climatic change, only apply to regions with the same climate or to areas within those regions. Indeed, as there are many climates, each in turn determining the boundaries of a climate area, and as climatic change is not distributed evenly one should like to know how each climate or one specific climate changes. How large such a 'climate area' is, is largely dependent on prevailing circulation types. This definition may in the context of risk assessment have as additional advantage that the prevailing weather types in a region, as determined by the prevailing types of circulation and determining climate, will be strongly related to the ecosystems and vegetation types in that region. Consequently, two geographical scales of interest were identified:

1) Regional (a region with a specific climate as defined by a climatic classification system, e.g. the Köppen System or the Holdridge Classification. Such a region may be very large indeed)
2) Local (an area within a climatic region).

list 2-6

An example of such a division is given in Figure 2.1. Based on well-defined climatic criteria, by which the link with prevailing circulation types is partly established, several climates can be distinguished in Europe. At this point the idea is put forward that if a risk assessment of climatic change in (a larger or smaller part of) Europe is the objective, the division as shown in Figure 2.1 may help in deciding what method should be followed to weigh the climatic risks for different parts of Europe.

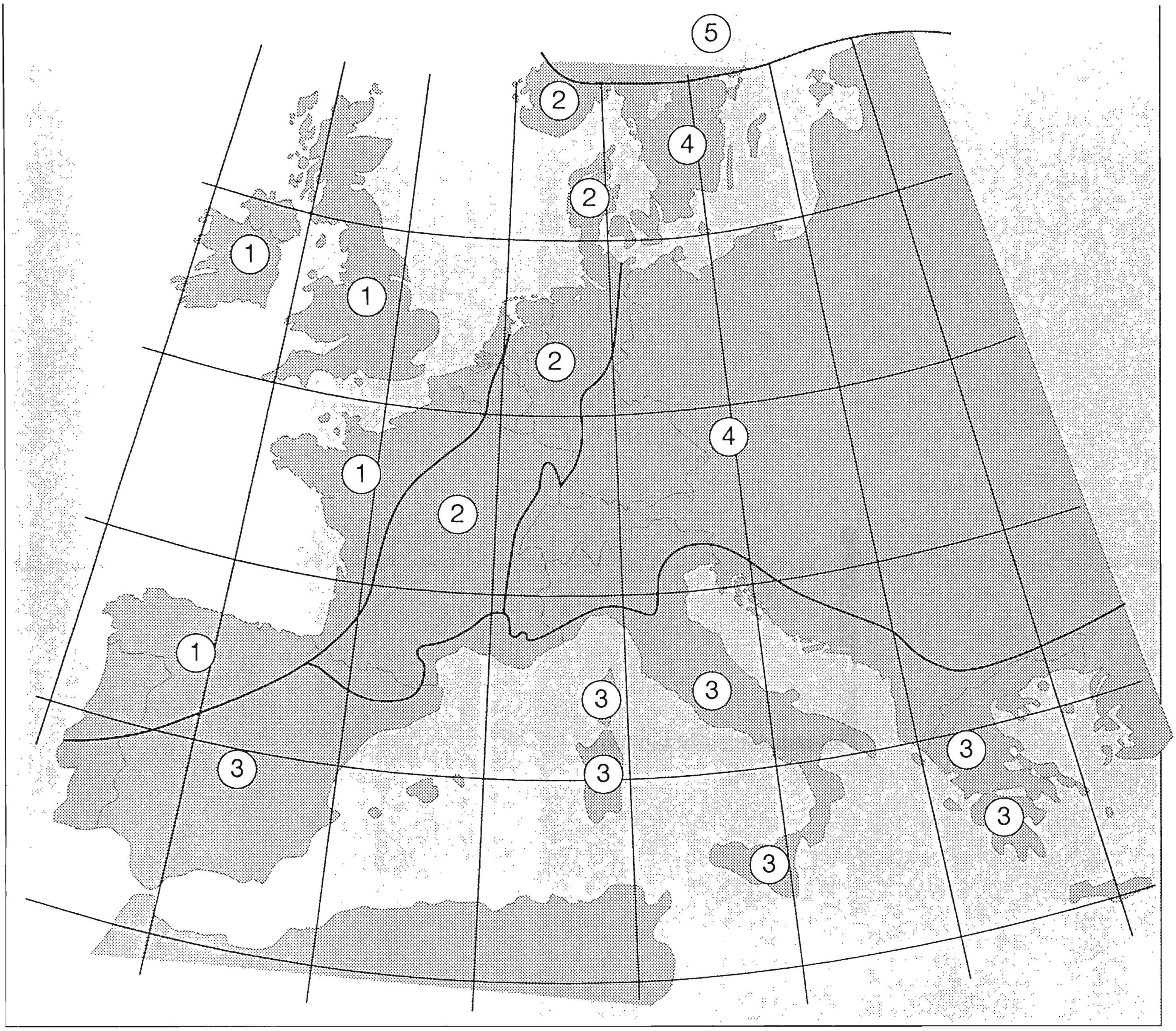

Figure 2.1. Modified Köppen climates for Europe. 1: oceanic climate ; 2: altered oceanic climate, 3: mediterranean climate, 4: continental climate; and 5: sub-arctic climate (First European Climate Assessment, ECSN 95).

2.3 What aspects of anthropogenically induced climatic change are of interest to society?

If a risk assessment of anthropogenically induced climatic change is the objective, it should be clear that:

1) the decision which risks, of all risks identified, will be probabilistically quantified determines implicitly the required temporal resolution of the global warming predictions,
2) there are two major mechanisms leading to climatic changes on regional scales, i.e. changes in greenhouse gas concentrations and changes in land use.

list 2-7

In this section it will be seen whether a closer look at the concept of 'change' may help us in being more specific about what kind of probabilistic statements are required for an assessment of the risks of a change in the climate.

2.3.1 What temporal resolution should we strive for when studying the risks of a climatic change?

If one is interested in studying climatic changes in the past then the temporal resolution of the records tells us what changes can be resolved. The Nyquist-theorem indicates that the sampling frequency should be at least twice as high as the highest frequency that should be resolved. So, if we are interested in past climatic changes occurring over time-spans of, say, 100 years we should have measurements with 50 year intervals. If we, on the other hand, are interested in future changes in, say, seasonal values, we need model output -if we wish to rely on model output, that is- with monthly resolution.

Climatic risks are often associated with changes in agricultural production. The cultivation of rice is, for example, highly dependent on maximum daily temperatures. If this is what one is interested in, even higher resolutions are required. Prediction of sea-level rise due to thermal expansion of the water, on the other hand, allows climatic information with a much lower temporal resolution.

Taking a basic idea about possible societal risks in the future due to a change in the climate as boundary condition for the question of what temporal resolution is required for the data to be used in a risk assessment of climatic change, the following options have been identified:

1) Annual values,
2) Seasonal values (by definition seasonal values should be climatological homogeneous, this implies that the number and location of seasons should be chosen appropriately),
3) Values of Julian days,
4) Day-time or night-time values.

list 2-8

It should be noted that even if data with the highest temporal resolution from the list is required, i.e. day-time or night-time values, it can be provided by the most complex climate model currently available.

2.3.2 What reference should we take if we talk about climatic change?

When discussing climatic changes, it is implicitly assumed that the climatic variable of interest, e.g. temperature, shows a temporal evolution or trend. However, climate does not change due to time, but because processes influencing climate directly or indirectly change in time -the internal climatic variability is disregarded at this point. In other words, it cannot be excluded that much more insight in the issue of climatic change can be gained if an appropriate reference is taken against which the climatic change can be measured. Two references were identified:

1) Changes in the concentrations of atmospheric constituents influencing the radiative balance. These changes affect climate globally, with regional variation due to uneven distribution of emissions of some short-living constituents like, for example, sulfur dioxide and soot;
2) Changes in land use. These changes affect the climate globally via changes in emissions and albedo. Land-use changes have a regional influence because they may influence the local heat-balance by the heat produced directly, e.g. by cities, and by changes in the albedo which influence the amount of incoming solar radiation used for surface warming. Changes in land use may also influence the hydrological cycle regionally.

list 2-9

Among the processes changing climate regionally a distinction can be made between direct influences and indirect influences. Processes influencing climate directly are changes in the hydrological cycle and direct temperature changes. Changes in run-off due to deforestation influencing in turn rain patterns and groundwater levels belong to the first category. Changes in albedo, resulting in the absorption of more or less heat, and the creation of so-called islands of urban heat belong to the second category. The direct effect is primarily regional, i.e. only extending to neighbouring areas.

Processes influencing climate indirectly via perturbation of the Earth's radiative balance are absorption and emission of long-wave or short-wave radiation by radiatively active gases, reflection and absorption of short-wave radiation by the Earth's surface and scattering of short-wave radiation by particles in the air, e.g. aerosols. The indirect effect is primarily global.

CHAPTER 3

Introduction to some important concepts

In Chapter 3 is made clear that:

1) future climate will never be predictable with an accuracy as required by policymakers;
2) the concept of probability can be given different meanings which may lead to different probabilistic statements even when the same evaluative basis is used; and
3) risks are better judged after recognition of the disproportionate effects of catastrophes and of the importance of incorporating uncertainty when calculating their probability.

list 3-1

3.1 Predictability of climatic change

When evaluating quantitative probabilistic statements about the future climate, one should not forget:

1) to check whether the question has been addressed if climate is predictable and, if so, to what extent,
2) that it is generally accepted among meteorologists that weather systems are fundamentally unpredictable over periods longer than two weeks,
3) that this unpredictability of the weather may from a fundamental point of view lead to the conclusion that the question how the statistics of climate will change under increasing concentrations of CO2 can only be addressed when the exact chronological order of changing climatic states is disregarded,
4) that new kinds of climate models or new and unconventional experiments with existing models may lead to a better, and possibly different, understanding of what may happen under conditions of double CO2.

list 3-2

The question whether climate is predictable and, if so, to what extent, though of considerable relevance, is not often being raised in the global warming discussion. There is no justification for that; predictability studies have been done since the beginning of this century (Richardson 22), receiving increasing interest since the 1960's. In addition, insight in the issue of climatic predictability may put the uncertainties with respect to the future climate in perspective. This may help decision makers which are active in the field of climate policy.

Classical predictability studies were largely concerned with the apparent stability of atmospheric flow patterns with respect to small amplitude perturbations. These would allow two or more highly similar patterns to evolve after a few days or weeks into highly dissimilar patterns. Thus, the atmosphere was treated as a large-scale manifestation of turbulence. More recent studies have often looked at specific features which show signs of enhanced predictability or specific occasions where overall predictability may be higher than normal. In addition, a far greater portion of the total effort has been devoted to predictability of climate: the predictability, at rather extended range, of time averages and other quantities which may be predictable even when the complete weather pattern is not. As weather and climate are two different concepts they need different approaches concerning predictability studies. Weather is often identified with the complete state of the atmosphere at a particular instant. As such the weather is continually changing. Weather prediction is then identified with the process of determining how the weather will change as time advances, and the problem of weather predictability becomes that of ascertaining whether such prediction is possible. For the current purpose, climate may be defined in terms of the ensemble of all states during a long but finite time span. Climatic prediction then becomes the process of determining how these statistics will change as the beginning and end of the time span advance, and climatic predictability is concerned whether, and if so to what extent, such climatic prediction is possible. To provide a better conceptual understanding of the predictability of climate, some attention will be given to predictability of weather first.

3.1.1 Weather predictability

Most meteorological time series are expressible as sums of periodic and non-periodic components. The periodic components include higher-frequency fluctuations like the normal diurnal and annual fluctuations, a weak lunar tidal oscillations and possibly other weaker low-frequency fluctuations, like those associated with changes in the Earth's orbital parameters, which have cycle lengths in excess of 1000 years, and in ocean circulation. When all these and other suspected periodicities are subtracted out, a strong non-periodic signal remains. This includes the progression of migratory cyclones and anti-cyclones across the oceans and continents, and it is unpredictable by any realizable procedure at sufficiently long term.

It has been established that, in view of the impossibility of perfect measurement, the predictability of any non-periodic time series decays to zero as the range of prediction becomes infinite. This result seems unexpected, because it implicates that prediction of atmospheric processes at sufficiently long range may be impossible, while the governing laws appear to be nearly deterministic. However, it follows from a fundamental theorem of predictability theory, which states that the behaviour of a system which varies non-periodically cannot be predicted at sufficiently long range, unless the present or some past state of the system is known with no uncertainty at all (Lorenz 63). The prediction of atmospheric processes, and thus weather forecasting and the simulation of future climate, could thence be seen as an initial value problem. The periodic component is, of course, highly predictable by pure extrapolation.

It should be stressed that non-periodicity, although an excellent indicator of unpredictability, is not a cause; it is a result. The immediate cause of the unpredictability of the atmosphere is its instability with respect to perturbations of small amplitude. That is, two or more slightly different states, each evolving according to the same physical laws, may in due time develop into appreciably different states. Since meteorological observations can never determine the state of the entire atmosphere exactly, it cannot be said which of a multitude of nearly identical states is the true present state. Consequently, the basis to predict which of a multitude of considerably different states will occur at some distant future time lacks. Thus, instability causes non-periodicity (Lorenz 63) and the lack of complete periodicity reveals itself in unpredictability.

The theory which assures us of the ultimate decay of atmospheric predictability does not give any indication about the rate of decay nor about the maximum range at which good predictions are possible. Studies based upon observed atmospheric behaviour or established atmospheric dynamics are necessary to estimate rate and range. It is such studies which have dominated the now-familiar subdiscipline of atmospheric predictability.

A classical predictability experiment is performed with a numerical model of the atmosphere. During a forecast interval, every several hours two or more numerical solutions, originating from slightly different initial conditions, are compared. The rate at which the difference between these solutions amplifies, together with an estimate of the likely difference between an observed and a true state, leads to an estimate of the range at which acceptable predictions are possible. Of course, the growth of errors slackens as the errors grow, and ultimately the errors become no larger than those made by randomly selecting a realistic atmospheric state as prediction. It has become common practice to measure the error which would be made by assuming one of these states to be correct, when in fact another is correct, by the difference between the two associated fields of wind, temperature, or some other element, and to express the rate of amplification of small errors in terms of a doubling time. In 1980s Lorenz (85) estimated the error doubling time to be slightly more than two days, which should be interpreted as the doubling time after the first day, but before errors have become too large. It might appear at this point that the range of acceptable weather forecasts could be extended by two days simply by reducing the observational errors to half their present size - a rather costly but not impossible task. However, the models used to estimate the doubling time do not explicitly contain smaller-scale features ranging in size from thunderstorms to dust whirls, whose amplitudes should double in hours or minutes or less.

The effects of these features upon the larger scales appear in the models, in parameterized form, but the uncertainties in these features do not. It is hardly expected that the details of the smaller-scale features will ever be revealed on a global basis by a regular observing network.
To quantify the possible range of weather prediction, Lorenz studied the process which seemed to be of greatest importance in causing unpredictability: advection. Advection can be defined as the transport of atmospheric properties by the motion of the atmosphere itself. A feature of advection is transport and distortion of small-scale phenomena by the larger ones, and simultaneous distortion of the larger ones by these small-scale phenomena. Perfect forecasting of just the larger-scale features would therefore require perfect representation and forecasting of the small-scale features. However, because they are too small for the models to resolve, they are parameterised. Parameterisation cannot be considered a perfect representation of physical processes. Consequently, errors in the smaller scales are introduced. These errors grow within a day to their limiting amplitudes (Lorenz 69). And while these amplitudes are not large per se, they result in temperature errors of one degree and wind errors of one meter per second in the larger scales after a day. The induced errors would then proceed to double every two days, just as if they had been present initially. From these results Lorenz estimated an absolute limit of about two weeks for forecasting day-to-day weather variations. Both this result and the fact that weather models and climate models can be considered as two different disguishes of one and the same model should be kept in mind when reading the following section.

3.1.2 Climatic predictability

Accepting the idea that the day-to-day sequence of weather cannot be predicted more than two weeks ahead, still it may be asked whether the next season will on the whole be warmer than normal. The benefits of such extended forecasts are clear, for at time scales of two weeks to three months the atmosphere has the greatest nonseasonal variance (Blackmon et al. 77, Dole and Gordon 83) that gives rise to economically catastrophic droughts, precipitation, heat waves deep freezes, and otherwise regionally anomalous weather events. In addition we may ask whether special circumstances may lead to forecasts at projection times of even longer periods. Admittedly, a giant step is made at this point. Here, the concern is not with how rapidly small errors will grow from their initial amplitude, but how slowly large errors will approach their limiting value. The theory which indicates that weather cannot be predictable at infinite range, in view of its lack of complete periodicity, also indicates that climate is not predictable at infinite range. More precisely, most climatic elements, and certainly climatic means, are not predictable at infinite range, since a non-periodic series cannot be made periodic through averaging. There need not, however, be any uniform limiting range of predictability of climate. For example, annual means could conceivably be predictable two years but not ten years in advance, ten-year means.....et cetera, to infinity, lack of periodicity notwithstanding. Again, non-periodicity does not indicate the rate of decay of climatic predictability. It can be said with near-certainty, however, that models which appear to give realistic results regarding the growth rate of small errors need not give much useful information regarding the approach of errors to their limiting values. After all, the processes, notably advection, which render the atmosphere unstable need not be the processes, if any, which hold the errors below their ultimate amplitude for extended periods.

Processes of the latter sort fall into two categories. First, there are those associated with some portions of the 'system' which, for physical reasons, behave more sluggishly than other. The ocean circulation is perhaps the most frequently cited feature which on shorter and longer time scales both influences and is influenced by the weather. And indeed, it has recently turned out to be possible to predict tropical ocean-atmosphere phenomena up to one year ahead based on anomalies in the sea-surface temperature (SST) of tropical ocean waters (Barnston et al. 94).

This ability is attributed to rapid advancement in data observing and assimilation systems, computer capability, and understanding of the ENSO phenomenon. The skill of these predictions has been calculated and in this respect these forecasts can be seen as probabilistic forecasts. Based on their calculated skill it has been concluded that they easily outperform persistence and they are thus regarded as useful. While these forecasts are at present not much better than forecasts based on regression models, they have great potential because they are dynamically based and because they predict atmospheric processes of which the consequences, e.g. severe droughts and floods, generally have a large socio-economic impact.

There are also some indications that current state-of-the-art models are able to simulate oscillations on larger time scales associated with the ocean circulation (Delworth et al. 93, Von Storch 94). Delworth et al., for example, have simulated spatial patterns of sea surface temperature anomalies associated with irregular oscillations of the thermohaline circulation with a time scale of about 50 years which bear an encouraging resemblance to a pattern of observed interdecadal variability in the North Atlantic. This resemblance may lead to the conclusion of both enhanced predictability of the future climate and additional difficulties when the aim is detection of anthropogenic climatic change.

Another slowly varying feature which should be considered part of the system, even though it is not influenced by the global system, is solar activity. Whether the sluggishness of variations in specific aspects of solar activity really leads to extended-range predictability has not been estimated yet; it is questionable whether enough observations are presently available and the computational effort is probably prohibitive. Of course, these difficulties also play a role when a GCM is used to determine how the ensemble of weather patterns occurring under current greenhouse gas concentrations would differ from the ensemble associated with twice current concentrations. In addition, the existing GCMs have been exhaustively tweeked to reproduce the current climatic system with a high fidelity. That does not mean that they are predicting the future climate in an exact way; a model cannot be tuned with information that is not yet there.

In general can be said that the coupled ocean-atmosphere system is prone to oscillations of different character on various time scales. Accurate simulation of these oscillations will lead to enhanced confidence in the future climate as simulated by climate models.

The other category of processes which could lead to extended range or climatic predictability is related to the phenomena of transitivity, intransitivity, and almost intransitivity. If the dynamics of a system leads to a unique stable set of infinetely-long-term statistics, i.e. a unique climate in the infinite sense, the system is called transitive. If, instead, there are two or more physically possible climates in the infinite sense, the system is called intransitive. Which of these climates will actually prevail forever in that case may be a matter of chance. It is not known whether our global system is transitive or intransitive, but both transitive and intransitive physical systems can be found which bear more than a superficial resemblance to the atmosphere. Of particular interest is a special type of transitive system where different sets of statistical properties may persist for long, but not forever. Such a system is called almost intransitive. Obviously, the climate of such a system may be highly predictable on restricted time horizons. Here a system is called almost intransitive when the slow variations of some statistic arise from some process which does not obviously demand slow variations - like SST does for instance. Based on the observations of the last million years, during which glacials alternated with interglacials, it has been conjectured that the global system is almost intransitive on a rather long scale. Consequently, the two climates would be the glacial and interglacial climates, while the transition from one climate to another would presumably occupy but a small fraction of the total time. If we suppose momentarily that these transitions are brought about only by some catastrophic processes, we can say that a numerical model which is correct except for omitting the catastrophes would be intransitive. Intransitive models may of course be much less elaborate. some of the simplest climatic models are intransitive, and in fact possess two steady-state solutions resembling glacial and interglacial climates.

It is difficult to determine whether almost-intransitivity really plays a significant role in the predictability of climate. Simple models will probably not yield the answer; it is too tempting to convert a simple transitive model into a simple intransitive model by changing the value of some empirical constant, whose value is in doubt in any case. Large GCMs would then have to provide the answer, except that the required length of the numerical simulations could be prohibitive. Meanwhile, there is much which can be said about the possible importance of almost-intransitivity.
Whether or not almost-intransitivity is present, slowly varying features such as SST patterns are present, and these may lead to ostensibly similar responses. Suppose that the importance of SST variations is being investigated. A climatic fluctuation due to almost intransitivity might be interpested as being due to SST effects, and a false positive conclusion would be drawn. On another occasion a fluctuation actually due to SST effects might be nullified by a superposed fluctuation due to almost-intransitivity, and a false negative conclusion would result. From this can be concluded that the more predictable the climate is when the interest is how the statistics of the climate of a region change with time if the system remains the same, the less predictable it is when the interest is how climate will change if the system will change due to an uncertain external forcing, for example by increases in the atmospheric CO2 content. It should be added that in the first case the chronological order is important, while in the second case it is known in advance that this order cannot be known because the timing and magnitude of the external forcing, e.g. increases in greenhouse gas concentrations, cannot be predicted.

If the interest is in the exact change of statistics, predictability would be enhanced by almost-intransitivity, or by slowly varying features such as SST patterns, which could lead to a relatively high probability that the coming time span would depart from the normal one in a known way. But to say that subsequent time spans are predictable is to say that they are not representative of the climate as determined from longer ensembles. Consequently, a numerical integration of one simulated time span would be insufficient for the purpose of estimating longer-term statistics. To investigate predictability of a climate under two times CO2 numerical integrations should ideally extend beyond the range of prediction of the chronological order of changes in statistics. Admittedly, this range could be infinite.

3.1.3 Climatic predictability and climate models

GCMs appear to be physically the most acceptable to study climatic predictability, but they suffer from slowness in execution. In general they run no more than two orders of magnitude faster than real time. To extend an integration of such a model from an interglacial to a glacial period would appear hopeless at present. Seen in this perspective the simple models, at the other extreme, seem attractive. To run such models for thousands of simulated years is no problem. Yet it can be dangerous to place too much confidence in models whose behaviour depends too strongly upon the details of parameterizations. For instance, a parameterization which fits the data rather well may become quite poor when extended beyond the range of data. This suggest that the modelling community might look more closely at models of intermediate size, which could perhaps be produced by reducing the horizontal resolution in some of the existing GCMs. For illustration, a decrease in resolution by a factor of two can speed up a model by a factor of ten.

Though most of the qualitative verbal arguments attempting to explain climatic change appear on the surface to contain nothing which cannot be duplicated numerically by manipulating a few hunderd numbers, these arguments assume on closer examination a basic knowledge of clouds and cyclones. So in order to duplicate these arguments GCMs must handle clouds and cyclones properly. At the moment, they do not.

A shortcoming of all models, particularly the simpler ones, is that they are too deterministic. The simplest models even possess steady-state solutions. One might argue that the global system is for pratical purposes deterministic, but certainly the portion which is observed, or which is represented numerically in a computer, is not by itself deterministic. Lorenz believes that the ultimate climatic models, and perhaps the first ones which will turn ice ages on and off, will be stochastic, i.e. random numbers will appear somewhere in the time derivatives.

3.2 Probability of climatic change

If the aim is to base a risk assessment of anthropogenically induced climatic change on probabilistic statements, it should be clear that:

1) all probabilistic statements which apply to real-life situations are conditional,
2) at least three fundamentally different interpretations of the probability concept exist,
3) it may on theoretical grounds be disputed whether it is possible at all to model the uncertain phenomena one is interested in,
4) the estimate of the probability that an uncertain event will happen may vary depending on the data which has been used to base the estimate on, and
5) a hierarchy of probability concepts can be established.

list 3-3

It has been made clear in the preceding section that it is not yet clear whether we will ever be able to predict the evolution of the climate for a specific place with accurate timing. What we do know is that we are not able to do this at present. At the same time, however, possible future climates can be either calculated, conceptualized or both. Policymakers working in the field of climatic change are eager to obtain the probabilistic information associated with these future climates. The expectation is that it will then be much easier to use the prediction that climate will change as a basis to propose measures to be taken. This report just aims at providing these probabilistic statements with respect to the future climate.

Because the concept of probability can, on different levels of understanding, be interpreted so differently, some basics concerning the foundations of probabilistic reasoning will be given first. All probability ideas, which can be traced back to the ancient Egyptians and Greeks, have contributed to these foundations.

3.2.1 The conditionality of probabilistic statements

To start with the notation, what does the sentence 'The probability that a person will die during a flight in an aircraft is one in a billion' mean? Well, that depends. The notation 'the probability that event X will happen' can be used either as a so-called 'absolute probability', in which officially nothing is 'given', 'taken for granted' or 'assumed' other than logic and mathematics (were that possible) or as a 'conditional probability', in which the probability of the occurrence of X is depending on one or more assumptions, for instance about future developments. Probabilities in practice are always conditional. In the example given the most important condition for the example to become reality is that the person to whom it applies will ever take a plane to go from one place to another. This principle of conditionality should be kept in mind while reading the remainder of this report. It implies, for instance, that probabilistic statements on global warming may change if we change the assumptions. And there are many assumptions as will be made clear in the following. Consequently, the value of probabilistic statements can only be judged properly when the underlying assumptions have been made clear explicitly.

3.2.2 Which interpretation of probability should be adhered to?

According to the foundations of probabilistic reasoning, one can discriminate between three interpretations of probability (Vlek 90):

1) The logical interpretation,
2) The frequency interpretation, and
3) The personalistic interpretation.

list 3-4

A short introduction to these interpretations is given here. In addition, the role of statistics in the different interpretations will be elucidated. The interpretation adhered to most often is the frequentist view, or frequency interpretation, of probability which is based on a notion of randomness and repeated experiments modelled by the sample space. In practice, this interpretation is based on past occurrences of other events of the same type or on experiments generating the events; the probability of a certain event is the limit of the relative occurrence of this event in an endless series of independent and equal observations of all events. Boundary conditions for this approach are that:

1) The system should be well defined,
2) Enough observations should have taken place of the event under consideration and of the circumstances under which the events have taken place, and
3) The observations should have taken place under similar conditions which will remain identical in the period of extrapolation.

list 3-5

The subjective or personalistic view of probability describes the strength of belief of an individual concerning the occurrence of events as result of an uncertain process. Strength of belief is determined through a process of introspection and manifests itself through overt choice or betting behaviour. The personalistic interpretation is based on the assumption that the appraiser is a rational decision maker who weighs the probabilities of different possible outcomes.

Logical probability presents an objective assessment of the degree to which an evidence statement (inductively) supports a hypothesis statement. The logical interpretation can also be defined as the inductive relation between a formally presented amount of information and the event. According to the logical interpretation can the probability that a certain event will happen be deduced from the characteristics of a system or process, e.g. from the symmetry of a die. The less simple the system under consideration and, thus, the description of the characteristics of the system, the more difficult it will be to produce probabilistic statements by this interpretation.

Statistics is the discipline that supplies the working basis for numerical probability with a frequentist interpretation. Statistics is also of value in supplying the basis for numerical probability in the subjective setting. Little is yet known about the practical issues connected either with formal concepts of probability other than the numerical one or with the logical interpretation of probability.

It should be noted that whichever interpretation will be used as a basis for probabilistic statements, in real life the interpretation chosen will always have been influenced by results gathered with other methods of interpretation. For example, an expert will base his opinion about the climatic change that will have been realised in, say, 2050 not only on his knowledge about atmospheric processes but also on what has happened in history and on model output.

3.2.3 Can uncertain phenomena be modelled?

A gap may be expected between the foundations of probability, to which the above three interpretations belong, and applied statistics; what kind of probability model can be used for which interpretation? Knowledge of the different interpretations of probability, though, can guide the selection of families of probability models (not necessarily numerical ones) so as to better reflect the indeterminate, uncertain, or chance phenomena being treated. Knowledge of the different interpretations may also clarify a choice among the divergent, conflicting statistical methodologies now current.

One should realize that different methodologic schools rely on different concepts of modelling probability, albeit this difference is obscured by common agreement on the mathematical structure of probability. Regarding the development of probability models for uncertain events, three different concepts are identified:

1) A model cannot be developed; Neyman-Pearsonians postulate that a class of uncertain phenomena, i.e. the 'unknown parameter', cannot be given a probability model,
2) A choice of models may be developed; Bayesians, personalists and subjectivists insist upon giving the unknown parameter an overly precise numerical probability model, but allow great freedom in the subjectively based choice of the model,
3) Only one, unique model can be developed; structuralists, fiducialists and maximum entropists carry the modelling process one step further by claiming to provide objective, rational grounds for the selection of a unique numerical probability model to describe the unknown parameter.

list 3-6

3.2.4 What data should be used as evaluative basis?

A domain contains both events whose occurrences are of interest to a scientist and a setting identified by the scientist as informative about the occurrence of events and as relevant to achieving its goals. In some fashion, the scientist decides that it can perhaps identify which of the events are probable, or which events are more probable than other events, or even assign a numerical probability to each event. Implicit in this process is an initial determination as to what provides the evaluative basis for the probability concept being invoked (e.g. what climatic records and theory can we use to calculate the probability of a climatic change in the next century). The evaluative basis largely fixes the meaning of the probability concept, which must have meaning extending beyond its evaluative basis if it is to serve a role other than that of data summarization. What evaluative bases can be distinguished according to the foundations of probability (examples from the atmospheric sciences between brackets)?

1) Past occurrences of other events of the same type (the palaeo-analogue method),
2) Experiments generating the events (output from simple climate models, e.g. autoregression models, or complex climate models, e.g. coupled-GCMs),
3) The strength of belief of an expert concerning the events (surveys of expert opinion or statements by individual experts),
4) The inductive relation between a formally presented amount of information and the event (due to the complexity of the climatic systm this method is not usually applied and, if so, often patronizingly called 'hand-waving').

list 3-7

1 and 2 belong to the frequency interpretation of probability, 3 belongs to the subjective interpretation of probability, and 4 belongs to the logical interpretation of probability.

Once the scientist has adopted a concept of probability supported by a domain of application, he or she then wishes to move this empirical relational system into a formal mathematical domain so as better to determine the implications of the position. The events of interest in the domain are represented either by sets or by propositions.

It is generally not possible to enumerate all possible events (complex systems occasionally surprise us by behaving in unforeseen ways) and therefore the sample space is at best a list of practical possibilities.
The recognition that probabilistic reasoning must confront a wide range of domains and levels of information, knowledge, belief, and empirical regularity can lead us to an acceptance of an hierarchy of increasingly precise mathematical concepts of probability. This hierarchy has been little explored, as almost all of the effort has been devoted to numerical probability. That numerical probability may be inadequate to the full range of uses of probabilistic reasoning is suggested by the following observations:

1) For some categories of empirical phenomena (e.g. climate) there is no obvious stability of relative frequency for all events of interest.
2) An ensemble of events may lack information; the resulting indeterminacy should be respected and not be obscured by applying dubious hypotheses (e.g. "If you know nothing about the parameter, then adopt a uniform maximum entropy for it").
3) Self-knowledge of individuals is intrinsically limited, and attempts to force belief or conviction to fit the mold of a particular 'rational' theory can only yield results of unknown value.

list 3-8

3.2.5 What precision in the probabilistic statements is required?

An attempt to accommodate to the preceding observations leads to the following hierarchy of concepts:

1) Possibly, the globe will warm by between 1 and 3 °C in 2050,
2) Probably, the globe will warm by between 1 and 3 °C in 2050,
3) That the globe will warm by between 1 and 3 °C in 2050 is at least as probable as that the globe will warm by between 0 and 1 °C in 2050,
4) That the globe will warm by between 1 and 3 °C in 2050 has a probability of between 4 out of 10 and 8 out of 10,
5) That the globe will warm by between 1 and 3 °C in 2050 has a probability of 6 out of 10.

list 3-9

Conditional versions of each of the foregoing concepts are also available and will in reality be the versions dealt with. An example of a conditional version of the foregoing concept is established when the following phrase is put before each of the five concepts: If atmospheric greenhouse concentrations continue to increase according to the IPCC IS92a scenario, then.....

The above five paragraphs bear four questions which should be addressed first by, in this case, policymakers as well as climatologists before the actual scientific work, which should result in quantitative probabilistic statements on global warming, can be started. In the following chapter results from studies leading to probabilistic statements will be reproduced. The information presented in this chapter should be used in order to judge the value of these statements.

3.3 Risks of climatic change

For a conceptual understanding of climatic risks which can be used in everyday life,

1) risks should be classified into three categories according to their event strength; and
2) it should be realized that the incorporation of uncertainty into probability calculations may avoid nasty surprises.

list 3-4

The term risk is used with a variety of meanings as there is no general valid definition. In its original meaning risk referred to the probability of loss. By experience the size of a risk is assessed according to the potential magnitude of the event. With the same probability the risk of continuing heavy rainfall appears to be greater over the basin of the Rhine than over the oceans because the potential scope of damage is greater in the former case.

The basic relationship between the two elements of a risk R, i.e. the probability P and the scope of the loss event S, is:

R is P times S, or $R = P \times S$

A risk is therefore greater the higher the probability and the higher the scope of the damage. Alternatively, a risk can be reduced to practically zero with consistently high scope by reducing the probability of occurrence. This corresponds in practice to all precautionary measures aimed at ensuring that nothing happens.

In this section about the concept of risk, the emphasis will lie at the risks of changes in extreme weather situations due to climatic change. There are many more conceivable risks of a change in the climate, like higher mean values for climatic variables without changes in extremes, but for a conceptual understanding of 'risk' it suffices to address only one kind of risks associated with a change in the climate.

3.3.1 A classification of risks

As the probability or frequency of extreme weather situations can only to a very limited extent be influenced by man, the only possiblity remaining to reduce the risks of such events is to reduce the scope in the case of something happening. In practice this procedure raises a difficult methodological problem. In order to take meaningful measures to reduce the scope probabilistic assumptions have to be used, even if the only objective is to distinguish between possible and impossible events, possible meaning that the probability is estimated to be larger than zero. This procedure reveals that up to a certain magnitude events cause no or only minimal damage, while stronger events can cause very great damage because protection is inadequate. Generally, an attempt is made to avoid risks due to all but the most improbable extreme events. However, never can all eventualities be accounted for because unexpected events can, by definition, happen at any time; there is no protection concept whatsoever that totally eliminates this risk. It is also true to say that there is no such thing as absolute safety.

At this point it should be acknowledged that an extremely rare event with a very high impact cannot be simply put on par with many frequently occurring events each with a rather low impact. The yearly averaged risk of a cyclone with a probability of once every ten years causing damage to 100 houses is, seen from a materialistic viewpoint, just as high as the risk of a once in a milennium event destroying 10.000 houses. However, it is not if other effects are also included. The incorporation of economical and political consequences and of mental anguish changes the picture as may be expressed by the following: one is an accident, the other is a catastrophe. The essential distinction between these two categories has to do with the quality of the loss and not with the quantity. Accidents can be dealt with by the affected system itself; catastrophes on the other hand call for outside help. Without this help catastrophes may lead to lifelong damage or, worse, to the destruction of the system.

Swiss Re, the Swiss Reinsurance Company, makes a distinction between three event classes (see Figure 3.1). Class A refers to events which give little or no damage based on existing protection; class B signifies events which cause more damage but which can still be dealt with, whereas events in class C lead to destruction of the system because the damage cannot be overcome (Swiss Re 94).
It is often assumed that it is possible to wait until climatic changes actually produce increased damage and that there is then still enough time left to react. This assumption is correct for class A events where an accumulation of weather related losses as a result of climatic change will quickly and clearly be reflected in the statistics and can be offset by corresponding measures such as higher financial provisions. It is a different matter with class B events. It may still be possible to deal with them individually but not if they occur in rapid succession. If the Midwest of the US would have been hit by another flood similar to that of 1993 in 1994 or 1995, the impact would have been quite different than if such a catastrophe were to recur only several decades from now. And if a class C event were to occur, a reaction is not even possible as the entire system would be destroyed. Such an event may occur in the future if a relatively low-lying developing country, e.g. Bangladesh, experiences the effects of the combination of rising sea levels, which will occur due to global warming, and a serious storm flood.
The problem is that observation periods are usually the only tool used to predict events. In that case only frequent events can be reliably predicted; the damage they cause is, however, slight. The probability of rarer or 'almost improbable' events can on the other hand hardly be calculated statistically, not even if the climate were to remain constant. However, the fact that an event has not yet occurred does not necessarily mean that it never will. This is especially true if the system under consideration is changing, like it is the case presently with the climatic system which changes with an unprecedented rate due to anthropogenic increases in radiative forcing.
The consequence of the above is that mistakes in calculating the probability or the change of frequency of class A events will have far less dramatic effects than those of class B and C events. The actual loss due to these effects is primarily determined by the assumed probability, simply because this assumption represents the conceptual basis for all measures taken to prevent loss. The loss will be higher the less an event is to be expected, in turn largely depending on the extent to which an event can be anticipated.

3.3.2 Reducing risks by the incorporation of uncertainty

Any attempt to calculate the probability of extreme weather events could potentially cause more harm than do good -all mathematical reservations notwithstanding- if the results of such calculations are wrongly interpreted. Although experts will always regard the calculations they have performed with caution, as they are familiar with the limits and intricacies of probability calculation, to the lay person -which in this case includes most politicians, decision makers and the public at large- the mere fact that the experts present calculations is proof enough to them that these probabilities can actually be worked out. So, if a dike is built of which the height is based on the calculated probability of a once-in-a-century flood, it should come as no surprise if town grow up beneath it whose lifeline depends on whether the weather actually complies with the parameters on which the calculation was based.

Probability assumptions do of course have to be made first if magnitudes are to be reduced. There is no point in heightening a dike on mere notion. What counts is the state of awareness with which the necessary assumptions were made. Regarding them as certain is resorting to false security. Thus, probabilistic assumptions are uncertain. In the context of a risk analysis uncertainty can be defined as either the situation that the possible future realisations of the system are unknown (non-structured uncertainty) or the situation that the possible future realisations of the system are known but that it is unknown what the realisation of the system will be at any arbitrary point in future time (structured uncertainty). So, whichever definition one wishes to adhere to, uncertainty points to the possibility of surprises. Consequently, if uncertainty is incorporated right from the start surprise effects can to a large extent be avoided. Technically speaking the avoidance of surprises requires two concerted actions (Figure 3.1). The steepness of the magnitude curve should be reduced by conceiving protection in such a way that it does not suddenly lose its effect from a certain event strength onwards. At the same time actions should be taken which may lead to large losses instead of catastrophic losses, if an event occurs which would have been catastrophic if these actions had not been taken. Probability considerations will not solve this problem; only the development of a clear concept of possible magnitudes, examination of the factors used to determine these magnitudes, and how these magnitudes can possibly be reduced.

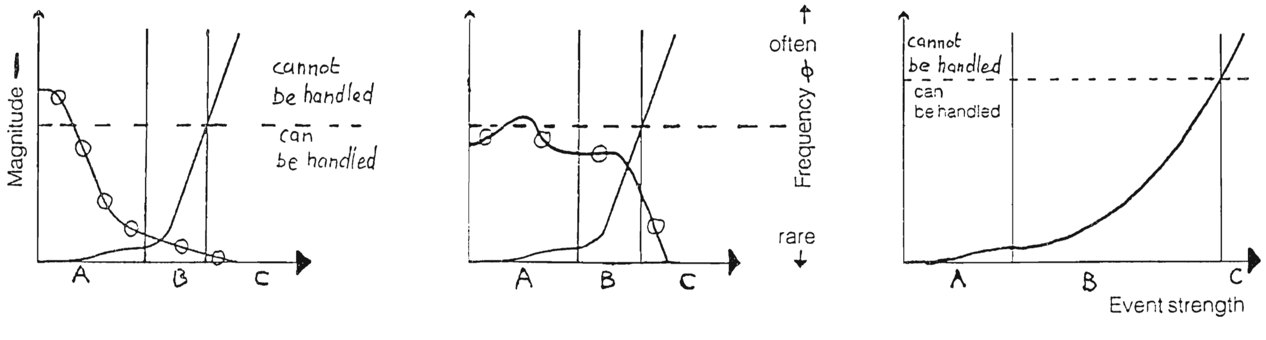

Figure 3.1. The visualisation of the three classes of events in the ideal case (left figure), in the case of a hypothetical change in the system (middle figure), e.g. due to a climatic change, and in the case of incorporation of uncertainty into the calculations of the probability of extreme events (right figure). Figure adapted from Swiss Re (94)

CHAPTER 4

Probabilistic approaches from the atmospheric sciences and from related and other disciplines

Chapter 4 will make clear that:

1) most quantitative probabilistic statements on the predicted climatic change done to date have been based on the analysis of time series,
2) as a consequence the interpretation method used most often to produce such statements is the frequency interpretation, and
3) the personalistic approach should be considered as a sound alternative to the frequency interpretation.

list 4-1

4.1 Introduction

This introduction will make clear that:

1) time series play an important role in probabilistic studies on climatic change,
2) a distinction should be made between time series based on observations and time series based on simulations,
3) the detection of a warming trend in the instrumental record may lead to enhanced confidence in the prediction of an anthropogenically induced global warming.

list 4-2

This study aims at addressing the following question in a quantitative way:

"What is the probability that climate will have been altered by a well defined change in temperature at some well defined point in the future due to well defined increases in atmospheric concentrations of radiatively active gases?".

This chapter identifies methods which can be used to come to an answer.
For several reasons -one of them being the conditionality of probabilistic statements referring to realistic situations- none of the methods leading to probabilistic statements will provide definitive answers. This implies that the answer on the question raised above may be based on results from several methods of probabilistic reasoning. By following this strategy more, or less for that matter, circumstantial evidence may be gathered enabling the rejection or acceptance of a hypothesis with more confidence. Each method, in turn, may be based on a different interpretation of the probability concept and may use another evaluative basis or tool. Two of the three known interpretations of the probability concept have been applied in the atmospheric sciences to produce probabilistic statements. These are the frequency and personalistic interpretation of probability. The remaining sections of this chapter have been classified accordingly. The evaluative bases used for the frequency interpretation all concern time series. Due to the subjective nature of the method, it is not clear what bases have been used for statements which belong to the personalistic interpretation. It seems logical, however, that time series play again an important role. For this reason some attention will be given in this section to the different kinds of time series.

4.1.1 Time series of climatic variables

Two kinds of climatological time-series can be distinguished; observed and simulated time-series. Most probabilistic statements on climatic change are based on statistical processing of observed climatological time-series or climatological records. There are two categories of climatological records. Records derived from measurements in real-time are called instrumental records. Records which are derived from proxy-data, which should be considered as indirect measurements, are called historical records. Proxy-data are obtained by analysis of, for instance, tree rings, air trapped in ice-cores and deep-sea sediments. The advantage of real-time measurements is that the data can be considered as accurate regarding errors introduced by instruments, abundant with respect to the number of meteorological variables that are measured, and that they have good geographical and timely coverage. A disadvantage is that the records are short with respect to their historical coverage; longest real-time temperature records date back to about the beginning of the eighteenth century. This disadvantage can be circumvented by using records from proxy-data.

These records have, seen from a viewpoint of their use for predicting human induced climatic change, no limit with respect to their historical coverage. Other characteristics of these records make them less suitable for probabilistic statements about climatic change. In general, these records are less accurate, cover less meteorological variables and give information about past climates on relatively small geographical scales only.
The other kind of climatological time-series is formed by output from climate models. These models, and especially the coupled ones, provide us with plausible climatological information on future and current climates on geographical and time-scales with comparatively high resolution and, in particular, good global coverage. The statistics on current climates varies in quality when compared with realistic data, but is for some regions and climatic variables quite acceptable. Admittedly, the accuracy of the information provided on future climates can only be determined a posteriori, but the fact that output from climate models is mentioned at this place serves only to illustrate that values based on simulations with models can be processed statistically just like values obtained by measurements in real time or via the analysis of proxy-data.

4.1.2 Anthropogenically induced climatic change in the recent past

This study focusses on probabilities of future climatic change. Even without having any knowledge about how the climatic system works may it be anticipated that the conclusion of this report will be that a climatic change in the future due to increases in greenhouse gases is very probable. Indeed, for the last, say, ten years this is what scientists, and the media accordingly, have been telling us. But it is also known that these greenhouse gas concentrations have been increasing since the beginning of the industrial revolution at the end of the eighteenth century. So it is legitimate to ask whether any trend can be discerned in the temperature record since the pre-industrial era. The conclusion that a trend can or cannot be detected in the climatic records since the pre-industrial era, and if so whether this trend can be associated with increases in greenhouse gas concentrations or other forcing mechanisms, may add to rejection or acceptance of the hypothesis that the Earth is on the brink of a greenhouse gas induced climatic change. Thence, a short account will be given of the analysis of time-series on trends in the following paragraph. However, trend analysis does not give the information this report aims at. So, the emphasis in this chapter remains on methods which have been used to obtain the latter, i.e. probabilistic information on future climates.

An examination of atmospheric CO2 data clearly suggests a fairly regular seasonal cycle around a marked increasing trend. In the case of global temperature data, however, any underying pattern is obscured by more irregular fluctuation. It is therefore not clear whether or not the observed changes reflect a statistically significant trend or other change. Moreover, the nature of the stochastic process generating temperature data is crucial to the statistical examination of a possible link between that variable and atmospheric CO2, or other greenhouse gases. If fluctuations in temperature are simply the random fluctuations of a stationary time series, then there is no genuine global warming trend to be explained, by CO2 concentrations or by any other cause. If there is statistical evidence of an increasing trend in global temperature, however, then there are a number of methods by which to investigate a possible relationship between two non-stationary series which may be applied. Thus, in the following section will be investigated whether statistical tests have established a trend in the temperature record since the end of the nineteenth century and, if so, if this trend is deterministic in nature or stochastic.

It is important the bear in mind from the outset the limitations of statistical tests. The tests are of use in answering the question of whether any changes in temperature over the period mentioned imply a statistically significant change in mean, or whether instead the observed fluctuations may legitimately ascribed to a sampling error. This question, while of considerable interest, is necessarily a narrow one.

The tests cannot tell us anything about fluctuations with a very long period, such that the temperature record fails to cover a full cycle. In general, it can only be hoped that can be determined whether or not sampling fluctuations are sufficient to account for the observed increase over the last century, ot whether instead it should be recognized that some underlying change has taken place, bearing in mind the possibility that the change could later be reversed as part of a longer cycle. It should be noted also that all statistical methods all have their own pitfalls. For instance, if the non-stationarity originates from a stochastic trend, this will not be elucidated satisfactorily when using a deterministic de-trending method.

4.2 Probabilistic statements based on the frequency interpretation

Probabilistic statements on climatic change have been relatively often based on the frequency interpretation because:

1) time series in general, which can be either simulated by climate models or based on observations and which are very well suited for this method, are to a large extent available,
2) there is reason to believe that time series simulated by GCMs give the best description of the future climate,
3) analysis of time series based on observations may give a good indication of the sensitivity of the global temperature for changes in CO2,
4) analysis of time series based on proxy-data may give a good indication of the sensitivity of regional climates for global mean temperature changes.

list 4-3

The frequency interpretation is based on past occurrences of other events of the same type or on experiments generating the events. In the atmospheric sciences both categories of information are often represented by time series. From a technical point of view can it be said that time-series analysis is most suitable for probabilistic statements. The concept 'time series' implies a set of data. In general, a data set can be processed statistically in order to obtain probabilistic statements. When statistical techniques are used causal relationships are estimated directly from time series, rather than that these relationships as known from physics are imposed, like is being done in GCMs.
The increasing interest in global warming has focussed interest on two time series: the monotonically-increasing concentration of atmospheric CO2 and the highly-variable global-average temperature series. Several methods in which a coupling between these two time series is established and which aim at probabilistic statements on climatic change have been identified. A division is made in this chapter between probabilistic statements based on time series representing real climates, which in the current situation can be either historical or instrumental temperature records, and probabilistic statements based on time series mimicking climates. The last category of time series is represented by temperature data which are generated by performing runs with large numerical simulation models, GCMs, and which describe either current or future climates, both in an equilibrium situation, i.e. no trend in forcing factors, and in a dynamical situation, i.e. a trend in forcing factors is imposed. But before going into future anthropogenic climatic change, some results on the significance of the observed climatic change during the last century or so will be presented.

4.2.1 The use of time series for probabilistic statements on climatic change

4.2.1.1 Has the climate changed yet due to human interference?

When the evolution of a time series can be expressed as the sum of a constant parameter and some random fluctuations this time series is stationary; when a time series can only be described by an expression of which the outcome tends to increase (or decrease) in time, the time series is non-stationary. In the last case should the time series exhibit a trend. The question of stationarity or non-stationarity of the instrumental global average temperature records has been addressed by many. There is general agreement that this record is non-stationary and that the underlying trend is upward.

The statistical literature on the detection of trends in time series makes a distinction between a series containing a stochastic trend, for which permanent changes in the distribution function depend upon relaizations of a random variable, and one containing a deterministic trend, for which the evolution of the unconditional distribution function over time is predictable. No studies could be found which provided evidence of a stochastic trend in the instrumental record of global mean-temperature data. At the other hand, several studies could be found in which evidence of a deterministic has been found (e.g. Galbraith and Green 92 and Richards 93). This finding of a statistically significant trend may be of particular significance in light of the observation that the general upward movement in temperature from the mid-nineteenth century till 1940 was followed by a period, which lasted until 1970, during which no apparent increase could be observed. It implies that the period of relative cooling falls within the range of sample fluctuation consistent with some significant positive trend. It is yet unclear whether the deterministic trend revealed is best approximated by a linear term or a non-linear term.
It should be noted, however, that the results cited imply nothing about the link between CO2 concentration and temperature. If an effect of greenhouse gases on temperature were present, it would not necessarily show up in the form of a change in trend over the instrumental period, i.e. from about the end of the nineteenth until today, but it could instead imply a uniform trend over the entire period of anthropogenically induced greenhouse increases, i.e. since the pre-industrial era. Paragraph 4.2.2 will address the question how the established trend can be associated with changes in CO2.

4.2.1.2 The use of time series based on observations

For probabilistic statements on climatic change based on time series which represent the real climate often relatively simple mathematical expressions are formulated which relate changes in a specific climatic variable -in all studies considered for this report this variable was the yearly mean temperature- to changes in one or more forcing mechanisms, among which greenhouse gas concentrations. By doing this, causal relationships are effectively established, e.g. between temperature and atmospheric concentrations of CO2. Then it is assumed that this relationship is robust, i.e. that it will hold if the value for the concentration of CO2 is extrapolated to a value that is outside the range of values on which the relationship is based. Thus, with an expression for the global mean temperature which includes a relationship between temperature and CO2 concentration, it should be possible to calculate the temperature for a two-times CO2 climate. Having established, in one way or another, such a relationship, it is relatively easy to provide probabilistic statements. Probabilistic temperature forecasts based on climatic records have in a direct sense -i.e., a (near) direct coupling between CO2 and temperature is assumed- been obtained by means of regression techniques and by a group-analogue forecast. Probabilistic statements which have been obtained indirectly -i.e. no direct coupling between CO2 and temperature is assumed- have not been found. However, the palaeo-analogue method has been used to estimate regional sensitivities for a well defined global mean temperature increase. Results of such a study will be presented in this chapter.

4.2.1.3 The use of simulated time series

GCM output has all the advantages you can think of when the aim is to produce probabilistic statements on climatic change with the aid of statistical techniques. For many climatic variables these models produce continuous series of values with a high time-resolution and unprecedented global coverage. The values calculated are easily reproducible and extremely consistent in both time and space. Moreover, they can be calculated for each point in time in the foreseeable future for any imposed changes in forcing factors. An important advantage over records of past temperatures is that the probabilistic statements based on the simulations in theory allow for a changing climatic system in which past relationships between two or more time series as established by statistical techniques, e.g. between changes in atmospheric CO2 concentrations and changes in global mean temperatures, are not valid any longer.

Main weakness of GCM output compared to the output of models which are fitted to observed values is that they reproduce instrumental records for some important climatic variables, in particular precipitation, badly. This devaluates their predictive power for these variables.
Probabilistic temperature forecasts based on simulated records have in a direct sense -i.e. a (near) direct coupling between CO2 and temperature is assumed- not been found. Probabilistic statements based on simulated records have been obtained indirectly -i.e. no direct coupling between CO2 and temperature is assumed. Results from a method will be presented in which regional sensitivities for a well defined global mean temperature increase have been estimated.

4.2.2 The use of output from General Circulation Models

Within the atmospheric sciences the general circulation models or GCMs are theoretically the tools most appropriate to predict the future climate. GCMs consist of a set of mathematical equations which incorporate time as a variable and which represent the atmospheric processes occurring in reality. Starting from an initial state which can be considered an accurate analogue of today's climates as they may be found all over the world, they are able to calculate future values for many climatic variables on a wide range of geographical and time-scales. GCMs do this by letting the processes, which determine the state of the atmosphere, evolve for a certain amount of computational time, e.g., an hour, which stands for a certain period of time in reality, e.g., a month. The resulting state of the atmosphere is then automatically used as initial state for the next computation, ad infinitum. When the values for the climatic variables, which are thus calculated again each time-step, are averaged over longer time-scales, information about the climate for the region and time-scale of interest can be obtained. Other accountable methods leading to the same results, i.e. global coverage of future regional climates, and which do not make use of output from GCMs do not exist. As GCMs are governed by physical laws, they are deterministic models. Consequently, these models give single values as output. When probabilistic information like skill-prediction, confidence levels, bandwidths or else is needed, this is only possible by processing results from more runs from either the same model or from different models alike. Nevertheless, output from GCMs has not yet been processed with the purpose to suit probabilistic studies. Several characteristics of climatic models and (thus?) of the climatic system can be held responsible for this.

I) GCMs can be strongly non-linear, resulting in the behaviour that small initial errors may grow larger very rapidly. This may theoretically lead to the situation that the uncertainty associated with a certain climatic state after, say, ten years has become so large that it is larger than the difference between two climatic states calculated from significantly different initial states after ten years. If, according to a specific model, this is the case with the Earth's climate under CO2 doubling can only be checked by performing an ensemble of runs with this model. Currently, computational resources are prohibitive in doing this with respect to time -computers are 'not fast enough'- and money -runs with coupled GCMs are very expensive. The future climate is generally calculated by these models by performing one run from a single initial state. Thus, it is difficult to retrieve how sensitive the model is for initial errors. Consequently, one may only guess what the spread in outcome will be for initial states which are different ánd easily distinguishable, and for different scenarios of greenhouse gas increases.

II) GCMs, and the climatic system for that matter, may exhibit chaotic behaviour. Chaos denotes a state of disorder and irregularity. The actual source of this irregularity is the property of the nonlinear climatic system of separating initially close trajectories exponentially fast in a bounded region of phase space of which the dimensionality is yet to be determined. It becomes therefore practically impossible to predict the long-time behaviour of these systems, because in practice one can only fix their initial conditions with finite accuracy, and errors increase exponentially fast.

If one tries to solve such a nonlinear system on a computer, the result depends for longer and longer times on more and more digits in the (irrational) numbers which represent the initial conditions. Since the digits in irrational numbers are irregularly distributed, the trajectory becomes chaotic. Lorenz called this sensitive dependence on the initial conditions the butterfly effect, because the outcome of his equations, which describe in a crude sense large scale weather patterns, e.g. extratropical cyclones, could be changed significantly by a small initial perturbation, e.g. a butterfly flapping his wings.

III) Model simulations exhibit chaotic behaviour in the sense that they may theoretically result in sudden changes from one climatic regime, e.g. an ice-age, to another climatic regime, e.g. an interglacial. The timing of these changes is, however, highly impredictable. Results of these simulations may on the other hand be less sensitive to differences in initial conditions as the probability whether a climatic state will occur may in the long run be controlled by a well defined mechanism which usually is conceptualized by one or more so-called strange attractors. The fact that glacial and interglacial climates remain for prolonged periods can be considered as evidence for the existence of strange-attractors in the climatic system. Some long simulations with coupled models reveal this kind of behaviour in the sense that some distinct climatic transitions take place and that an altered climatic state may endure for a long period of time (Figure 0). It should be noted that nonlinearity is a necessary, but not a sufficient condition for the generation of chaotic motion.

For probabilistic statements which can be used in the daily practice of policy making, results are needed with a realistic timing. Most GCMs calculate what the temperature change for a CO2 doubling compared with the present day situation will be if the atmosphere is in radiative equilibrium. Thus, this temperature change will only occur if a new radiative balance is established. Because CO2 has a long atmospheric residence time -one century typically- and oceans have a retarding effect on the establishing of the equilibrium temperature on yet unknown, but possibly much longer, time-scales and because it cannot be foreseen when anthropogenic emissions will stabilize, equilibrium results are not very useful (for a more elaborate foundation of this statement, see IPCC 90). Coupled GCMs, in which a coupling has been established between atmosphere and ocean circumvent this problem. They are able to calculate the warming in time -which is only a percentage of the committed warming- and so could be in principle used for probabilistic statements. As GCMs do not produce these statements themselves, they should be produced either by processing the numerical output for each time step of some runs with one and the same model or by processing these outputs of many models having performed identical experiments, i.e. same initial conditions, same rate of CO2 increase or perturbation, et cetera. However, because coupled GCMs require large computative resources and a large team of scientists and technicians for up-dating and maintenance, coupled GCMs are only few. At present about five exist. In addition, because runs on these models are, as mentioned, extremely time consuming and expensive, not many runs have yet been performed. Both facts lead to a scarcity of output which could be statistically processed for probabilistic statements. This may explain why probabilistic statements based on direct numerical output from coupled GCMs could not be found. Probabilistic statements based on averaging of averaged output of more models could be found though. But these results do not capture the full characteristics of the future climate as predicted by the coupled GCMs. In addition, this kind og averaging assumes a normal distribution of the simulated climatic states. It is highly questionable whether this is a correct assumption.

Concluding one could say that while coupled GCMs are accurate tools on the one hand to calculate future climate with an associated probability, there are on the other hand still too many problems, both on a theoretical and a practical level, that have to be solved before these models can be used to produce probabilistic statements with restricted bandwidth.

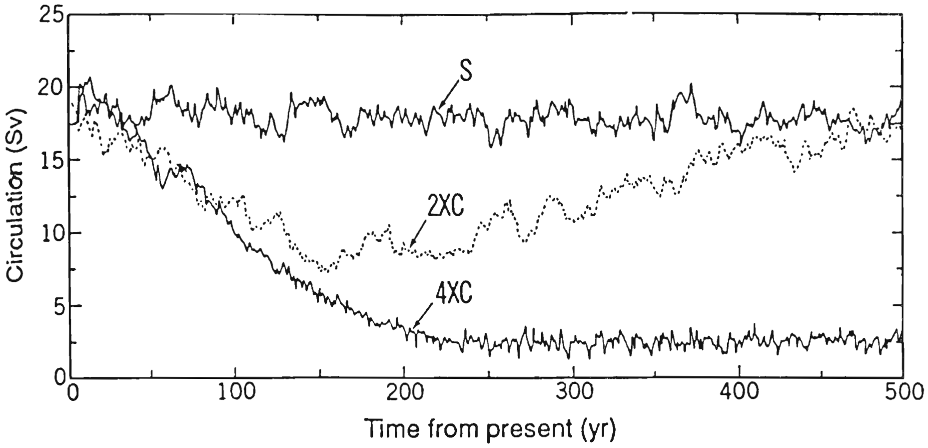

Figure 4.1. Temporal variation of the intensity of the meridional circulation in the North Atlantic ocean for the present climate (S), a double-CO2 climate (2XC) and a four times CO2 climate (4XC) as calculated by a coupled-GCM (Manabe and Stouffer, 93 and 94).

4.2.3 Regression models

Regression models for probabilistic statements about future climate are statistical models which are founded upon the assumption that the record of a specific climatic component, e.g., the global-mean temperature, can be explained with a certain accuracy, which should be determined in advance, by using much less variables than are actually involved in determining the exact value of this component (regress can, in this context, be defined as return to a more primitive form). In other words, creating a regression model one starts with the hypothesis that the influences of different forcing mechanisms can be separated when analysing temperature records or records of other climatic variables. A forcing mechanism can be defined as a mechanism which makes that the value of a certain climatic variable, e.g. temperature, at a given place and over a certain period of time exceeding the characteristic time scales of weather, deviates from its long-time average for the respective period.

Forcing mechanisms are the solar cycle, volcanic activity, aerosols, ENSO (1), greenhouse gases, et cetera. If the influences of some forcing mechanisms on, for instance, temperature can be distinguished from each other via mathematical expressions, a statistical model can be set up with parameters for these mechanisms. Some forcing mechanisms are difficult to distinguish from each other. For instance, modelling the effect of industrially emitted aerosols is difficult both due to the lack of historical data and because of collinearity with trace gases. Since the industrial activity that emits sulfur particles is the same process that gives rise to the greenhouse gases, the damping effects of these aerosols on temperature may be impossible to distinguish statistically from the radiative trapping activity of the trace gases, at least over short time-horizons.

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[1] ENSO can be considered as an internal climatic fluctuation that may be regarded as a stochastic free non-periodical oscillation of the ocean-atmosphere system. ENSO consists of two components.
The first component is El Niño (La Niña), in which the sea surface temperatures over the entire eastern equatorial Pacific Ocean show a warming (cooling) of several degrees. Associated with these changes are anomalies in the ocean circulation. A strong El Niño (La Niña) can have a cooling (warming) effect on the annual global mean temperature of about 0.2 °C.
The second component of ENSO, the Southern Oscillation, is mainly atmospheric. It is associated with large east-west shifts of mass in the tropical atmosphere between the Indian and West Pacific oceans and the East Pacific ocean. These are two components of one global scale oscillation. ENSO events occur every three to ten years and are known to have far-reaching climatic and economic consequences on large geographical scales.

As a result, in the regressions considered for this study the effect of industrial sulfate emissions, which are excluded from the equations, will be loaded onto the elasticities for CO_2, which are therefore likely to be reduced somewhat from the values implied by the radiative properties of the gas. Over longer time-horizons, however, the fact that the atmospheric lifetime of sulfates is shorter than that of trace gases may give rise to extreme nonlinearities in the response of temperature, in which the effect of trace gases is temporarily damped until industrial sulfates precipitate. In addition, recent results indicate that the climatic sensitivy for forcing due to aerosols may well be different from the sensitivity for forcing due to greenhouse gases (Taylor and Penner 94). If so, this will make the results models which have not incorporated this knowledge less accurate.
Suppose now that a regression model, with parameters for several forcing mechanisms, has been created. If we know the timely evolution of the different forcing parameters, e.g. by informing data banks, the model should be tested by mimicking the climatic record from which it is indirectly derived. If it is accurate in reproducing this record can it be used for statements about the influence of increased greenhouse gas concentrations on current global temperatures. The model can in addition be used to predict future warming by increasing the values for the greenhouse parameter(s).

4.2.4 Forecasts based on analogues in the past

The group-analogue forecast method obtains probability forecasts by analysing the behaviour of certain variables in analogue groups statistically. This method is taken and adapted from synoptic meteorology where the term analogue is defined as a past large-scale synoptic weather pattern which resembles a given current situation in its essential characteristics. The use of analogues as an aid in forecasting is based upon the assumption that two similar synoptic weather patterns will retain a similarity through at least a short period of further development (American Meteorological Society 59). With respect to climate change a group analogue could be defined as the mean climate deduced from a number of climates which prevailed during periods which were separated in time but which did have the same atmospheric greenhouse gas concentration.
The palaeo-analogue method aims at identifying similarities among different warm or cold periods as they can be inferred from historical records. The basic assumption of the palaeo-analogue forecast is that the globally averaged mean annual temperature, being an integral energy characteristic of the planet, is the key climate parameter that determines in first approximation the large scale structure of the temperature and precipitation distribution under equilibrium. If this hypothesis verifies, palaeo-analogue reconstructions of past warm or cold epochs may under certain conditions be used to get a notion of future regional climatic change.

4.2.5 Time-series analysis and probabilistic results

Regression models and the forecasting method based on analogue groups have in the present context as important advantage that the predictions obtained implicitly contain stochastic information. Regression results feature stochastic information because the modeller aims at fitting the observed curve in the most accurately possible way. This is quantitatively made clear by small(er) standard errors. These errors determine the confidence limits of the predictions. Thus, a probabilistic outcome is generated.
The group-analogue method aims at identifying as many occurrences of a well defined event, e.g. a 5% rise in atmospheric CO2 concentration over a certain period of time, as possible. If this information is combined with information for another variable, e.g. temperature change, over the same period, it will be simple to derive stochastic statements for this other variable. Put simply, if in 20 of the 50 cases in which a 5% CO2 rise occurred, the temperature change was less than 1 °C, it can be said that there is a 40% chance that temperatures will not exceed 1 °C for a 5% CO2 increase.

The palaeo-analogue method should be considered as providing sensitivities of regional climates to a global mean warming only. Information which can be extracted from palaeo-climatologic data concerns mainly magnitudes of regional warming for a global warming of, say, 1 °C.

One serious discrepancy between results from this method and the two other methods mentioned is that the palaeo-analogue method is based on climates which are in a state of equilibrium only. For the foreseeable future, the currently changing climate will not reach an equilibrium state. This fact questions the value of palaeo-climatologic results for the present study.

4.3 Probabilistic statements based on the personalistic interpretation

The use of the personalistic interpretation for probabilistic statements results in subjective probabilities which:

1) are assumed to be based on well-considered mature judgements,
2) are quantitative and interval valued, and
3) can be measured by the linguistic method, i.e. a person is asked to make an estimate, and by the behavioral method, i.e. a person has to make bets.

list 4-4

If you wish to attach a probability to a prediction, you are usually forced to use subjective probabilities, here taken as a synonym for 'degrees of belief'. Sometimes 'degree of belief' is interpreted as based on a snap judgement of a probability, but it will here be assumed to be based on a well-considered mature judgement. This perhaps justifies dignifying a degree of belief with the alternative name 'subjective probability'. It has been shown that a theory of subjective probability provides help in arriving at mature judgements of degrees of belief. It does this by providing criteria by which inconsistencies in a body of beliefs can be detected.

Although subjective probabilities vary from one person to another, and even from time to time for a single person, they are not arbitrary because they are influenced by common sense, by observations and experiments, and by theories of probability. It may be stated that sampling is just as important in subjective statistics as in sampling theory methodology.

Beliefs can be more or less strong. Often one degree of belief exceeds another one. Beliefs, then, are quantitative, but this does not mean that they are necessarily numerical; indeed, it would be absurd to say that your degree of belief that it will rain tomorrow is 0.6547. One reason why degrees of belief are not entirely numerical is that statements often do not have precise meanings. For example, it is often unclear whether a person entering a room with wet hair has just taken a shower, just perspires or comes in from the rain. Even when language is precise, it must still be recognized that degrees of belief are only partially ordered. They may be called comparative probabilities.

By allowing for the sharp landmark probabilities provided by games of chance, each subjective probability can be enclosed in an interval of values; so we may regard subjective probabilities as interval valued. This leads one to talk about 'upper' and 'lower' subjective probabilities. These are defined as the right-hand and left-hand end points of the shortest interval that is regarded as definitely containing a specified degree of belief. The upper and lower degrees are liable to be fuzzy, but this is at any rate more realistic than sharp or precise degrees. Thus a theory of partially ordered probabilities is essentially the same as a theory of probabilities that are 'interval valued'. A degree of belief can be regarded as depending on propositions that might describe events. A proposition can be defined as the meaning of a statement, and a subjective probability always depends upon two propositions; 'the subjective probability of A given B'.

The assessment of subjective probability distributions is a demanding task, even for assessors which should be considered as experts in the field of statistics (see Cooke 91 for a general introduction to the use of subjective probability in science, and Van Lenthe 93 for an efficient method for eliciting subjective probability distributions). The two primary methods for measuring subjective probabilities are linguistic and behavioral. In the linguistic method a person is asked to estimate a probability, and in the behavioral method he has to make bets, although the stakes need not be monetary. He has to put his decisions 'where his mouth is'. Conceivably, this principle constitutes a threat to the use of confidence intervals.

Several probabilistic statements based on the personalistic interpretation have been found: some based on a survey of expert opinion and some statements by individuals. The survey of expert opinion that has been found was based on the linguistic method; the statements by individuals were based on both the behavioral approach and the linguistic method.
A survey of expert opinion is often called a 'Delphi approach'. In the context of climatic change, this method aims at eliciting subjective probabilities for the occurrence of specified climatic events by a survey of an undefined number of climatologists ('experts'). For this, individual quantitative responses to several questions are weighed according to expertise and then averaged. This method of aggregation ideally preserves the experts' collective uncertainty about future climate trends. The aggregated subjective probabilities can subsequently be used to construct possible future climate scenarios, each having a 'probability' of occurrence. It is then also possible to compare the aggregated probabilities of contingent events from scenario to scenario, across latitudinal bands, and by time periods.
Accountable individual opinions containing probabilistic statements have been found also. Testimonees for state authorities, for instance, belong to this group. They should not necessarily be worse or better than the weighed opninion of a group of experts, be it that individual opinions are less well controlled and controllable.

Possible advantages of this kind of intrinsically subjective methods are
I) that state-of-the-art knowledge of the climatic system is accounted for in the opinions,
II) that is compensated for known flaws in other methods,
III) that it comprises results from many other approaches,
IV) that it is a comparatively fast method, and
V) that virtually all kinds of information can be obtained.

Disadvantages are
I) that it remains a method of which the results can hardly be reproduced, part of the reason being that knowledge is increasing continuously, and
II) that the results are based on mental processes of which no reliable, in the sense of reproducible, test procedure is known.

CHAPTER 5

Quantitative probabilistic results from studies on global warming

In Chapter 5 only the quantitative results from probabilistic studies are presented. This has been done to make clear what kind of quantitative probabilistic results can be obtained from methods which already exist and which have been identified in the foregoing chapter. It will be made clear that:

1) simulated time-series indicate univocally that climate will change significantly due to increases in the atmospheric concentration of CO2,
2) records of past temperatures indicate univocally that temperature will increase significantly due to increases in the atmospheric concentration of CO2, and
3) experts share the opinion that the climate will change in line with the predictions from climate models.

list 5-1

5.1 Probabilistic statements based on simulated time-series

Output from a limited amount of runs with General Circulation Models indicates that:

1) the trend of a global warming of about 0.5 °C during the last century is more than can be explained by natural, or internal, variability alone,
2) precipitation may change substantially in Europe under conditions of global warming, and
3) climate, including exceedance probabilities for annual snowfall and river ice coverage, may change significantly in Canada.

list 5-2

The basis for many discussions as well as impact studies on climatic change is that GCMs indicate that the Earth may warm with an unprecedented rate. GCMs differ to a large extent in their predictions with respect to the magnitude of this warming. Indeed, it can be stated that the smallest warming calculated with GCMs is an order of magnitude lower than the largest calculated warming, i.e. about 0.5 °C versus about 5.0 °C. Many model runs with both simpler and more elaborate GCMs have yet been done. To date none however has produced probabilistic outcomes. A simple method to produce such results, albeit not necessarily a good one, is the statistical processing of GCM results. Two such studies could be found; one using simple averaging methods to obtain probabilistic results, the other based on stochastic models which used GCM output data as input.

Another method to come to probabilistic statements is the assessment of the role of natural variability in recent global warming with the help of coupled models. For this, the models should be integrated over century-long periods, keeping unchanged all thermal forcing factors such as the solar constant and the atmospheric CO2 concentration. This will result in a time series of global mean surface air temperature which should be considered a realistic presentation of natural, internal variablity. If so, one may compare the largest simulated trends with the current trend of about 0.5 °C during the last hundred years. If the simulated trend is smaller this may lead to the conclusion that the observed trend is attributable to external forcings, e.g. an increase in atmospheric CO2. This kind of research is on-going and preliminary results indicate that a statistically significant externally induced warming has been observed, assuming that the models reproduce the internal climatic variability accurately (Stouffer et al. 94, and Hegerl et al. 94). Hegerl et al., to give an example, state with 95% confidence that the latest observed 20-year trend of near surface temperatures (1974-93) cannot be explained by natural variability alone.

5.1.1 Averaging of GCM output

In a study by Viner and Hulme (undated and non-refereed), warming predictions for each grid-box were for seven GCMs expressed as fractions of their model sensitivities for a CO2 doubling. This was done to remove the bias introduced by the differences between these sensitivities. These fractions were averaged to give a best guess standardised temperature change scenario ΔT^* for each grid-point. As a measure of uncertainty they calculated the unbiased estimate of the standardized model-to-model standard deviation. They assumed that the sample of seven models was normally distributed in order to calculate the upper and lower confidence limits about ΔT^*. A similar procedure was followed for monthly precipitation, an important difference being that a weighting based on the pattern correlation coefficient between the observed and simulated control run precipitation fields was introduced; GCMs which better simulated current precipitation carried more weight in the climate change scenario.

The uncertainty, i.e. the distance between the lower and upper 90% confidence limits, was determined in the same way as for temperature with the assumption that the sample of seven models represents a Gaussian distribution. The resulting 80% confidence interval is considerably wider for precipitation than for temperature reflecting the much greater model-to-model variability in regional precipitation change patterns generated by GCMs.

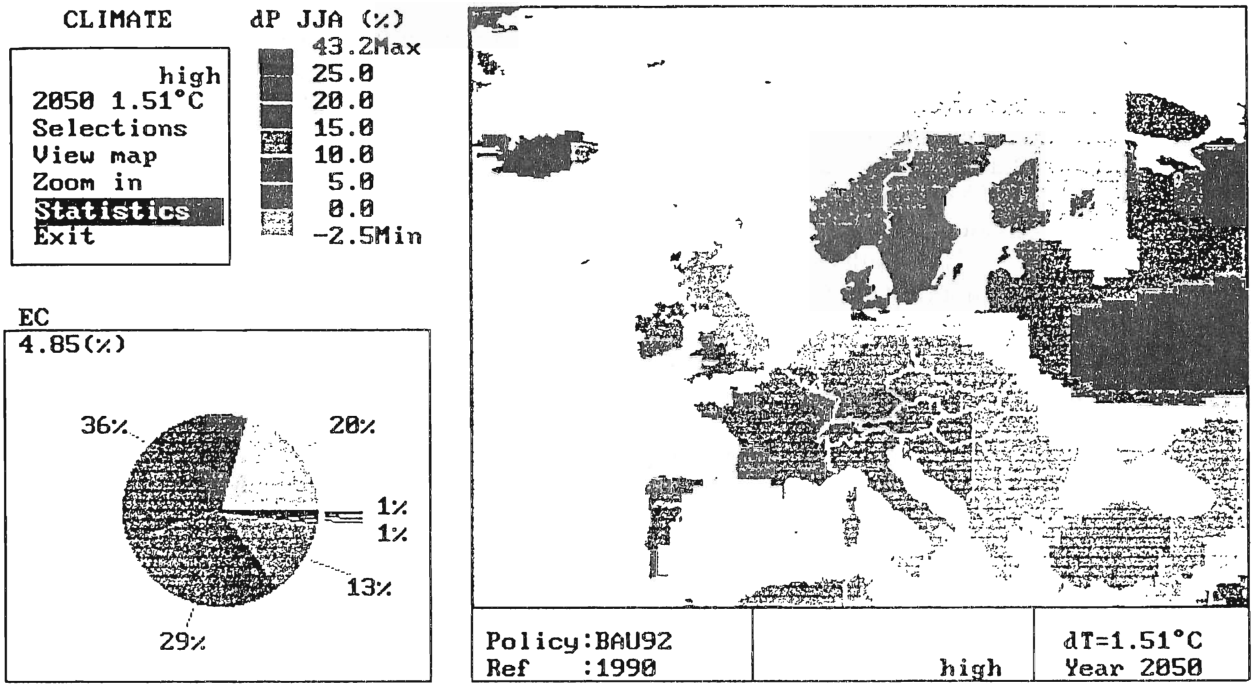
Results for the upper and lower 90% confidence limits precipitation scenarios are presented in Figure 1; the scenario High refers to the upper 90% limit of predicted precipitation change during summer for a global warming of 1.51 °C (up to 43.2% increase in precipitation), Low refers to the lower 10% limit (up to 61.2% decrease in precipitation).

This procedure effectively leads to detailed information about the patterns of regional temperature and precipitation change for a given global temperature change. So, this study can be considered as a sensitivity study. However, although GCM output -the GCMs used calculated global steady-state warmings of between 2.7 and 4.8 °C for a doubling of CO2- is used as basis to generate these patterns, the probability of the global warmings calculated has not been not discussed. This leaves the possibility that they all make the same mistakes and, thus, all present a wrong picture about climates under two times CO2.

PRECIPITATION CHANGE SCENARIOS FOR EUROPE IN THE YEAR 2050 UNDER A BUSINESS-AS-USUAL SCENARIO

(VINER AND HULME, UNDATED)

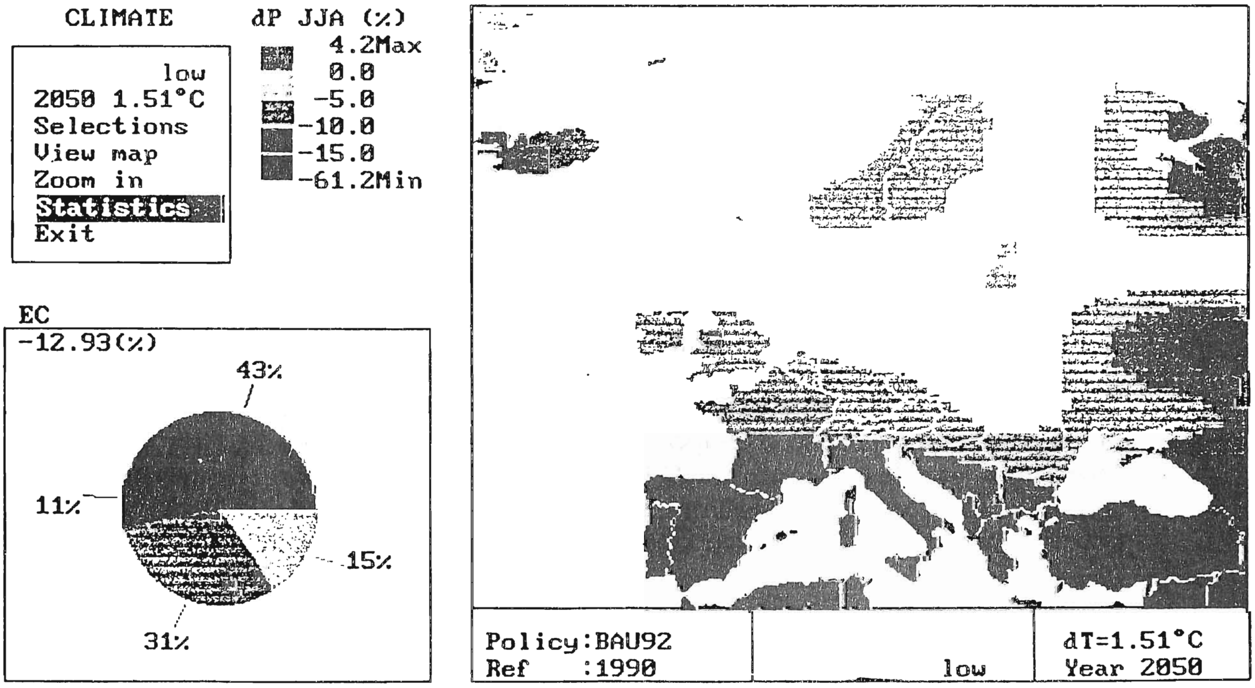
Global-mean temperature change in 2050 with respect to 1990 is assumed to be +1.51 °C



EC
4.85(%)

Policy:BAU92
Ref :1990
high
dT=1.51°C
Year 2050

Figure 5.1a. Under the precipitation-change scenario High, which is the upper 90% confidence limit of the precipitation changes calculated in a probabilistic way, the EC-wide precipitation increase (dP) during summer (JJA) is just under 5% (see pie chart).



EC
-12.93(%)

Policy:BAU92
Ref :1990
low
dT=1.51°C
Year 2050

Figure 5.1b. Under the precipitation-change scenario Low, which is the lower 10% confidence limit of the precipitation changes calculated in a probabilistic way, the EC-wide precipitation decrease (dP) during summer (JJA) is just under 13% (see pie chart).

5.1.2 GCM output used as input for stochastic models

Woo (92) showed that stochastic models can be used to extend time series and to enable the simulation of other forms of geophysical data which may not be available. Parameters from a 32-year long temperature and precipitation record (Figures 5.2a and c, respectively) were used to simulate 100 years of daily temperature and precipitation data by means of a stochastic model. Subsequently, mean monthly temperature and precipitation changes as predicted by three GCMs for a two times CO2 climate were introduced in the simulation models to produce 100 year of daily values that reflect the three GCMs' scenarios . As an example, the summary statistics for temperature extracted from 100 years of simulated data based on one of the GCMs is presented in Figure 5.2b. The simulated result clearly indicates rises in the mean daily temperatures in accordance with the GCM scenario.

A similar calculation for precipitation increases in a two times CO2 climate is presented in Figure 5.2c. The results show that the stochastic models can easily translate the GCM yearly and monthly changes into a finer time scale resolution.

Probabilistic results were also obtained for annual snowfall distributions as well as for the amount of days that the ice cover of a certain river lasts, both under CO2 doubling. Using historical records of temperature and precipitation, the probabilities of snowfall of different magnitudes were obtained. Then, daily snowfall was allowed to change according to the GCM scenarios, using the daily temperature and precipitation simulators. The result is presented in Figure 5.2d. Note that the conclusion from the results of the three models should be that annual snowfall at Norman Wells will increase under a two times CO_2 climate. This is contrary to what many from intuition believe will happen. However, the obvious lack of agreement amongst the results derived from the three models concerning the snowfall distribution illustrates the difficulties of predicting future hydrologic events given the then current status of GCM model outputs.

Climate change scenarios were applied to river ice cover data, which were calculated from a degree-freezing day approach, to estimate the probabilities of various ice-cover durations and thicknesses under a doubling of CO2. Figures 5.2e and f quantify the impact of warming on the shortening of the ice-cover season and the reduction of ice-cover probabilities: climatic change will considerably reduce the significance of the river ice cover.

One of the conclusions of Woo is that simulated temperature and precipitation data can be used as input variables to derive probabilistic hydrologic information through the use of deterministic or probabilistic relationships. The snowfall simulation exemplifies the use of a simple deterministic relationship between precipitation and temperature, and the example for ice-cover simulation is an application of the probabilistic relationship between air temperature and ice-cover initiation or decay.

This kind of stochastic modelling does not produce probabilistic statements about the order and magnitude of global warming. This is primarily so because appropriate time series of greenhouse gases versus temperature do not exist. So, these models rely on the output of GCMs. GCMs do not generate probabilistic statements. As with the above-mentioned results of Viner and Hulme, in the present context should this be considered as a serious omission: probabilistic statements with respect to changes in precipitation with changes in temperature loose some of their value if they are not associated with a probability for this change in temperature. What this kind of modelling does provide, however, is an idea about the change in extreme events in a probabilistic sense.

CLIMATIC CHANGE SCENARIOS FOR NORMAN WELLS, CANADA, UNDER CO2 DOUBLING

(WOO 92)

Figure 5.2a

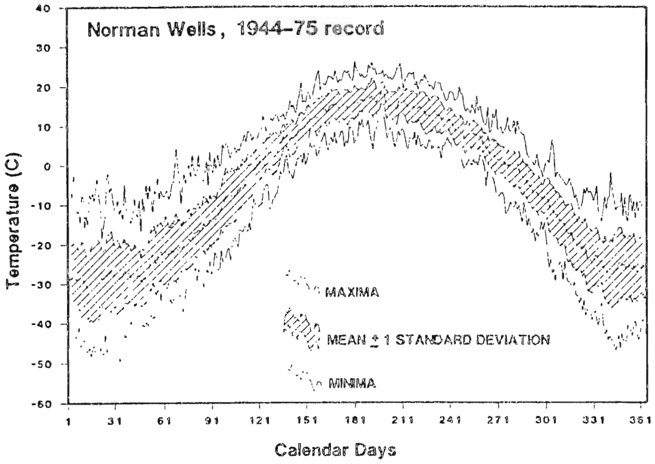


Figure 5.2b

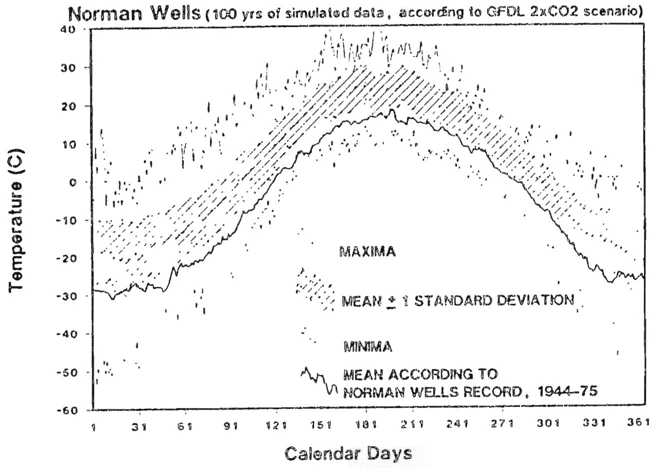


Figure 5.2c

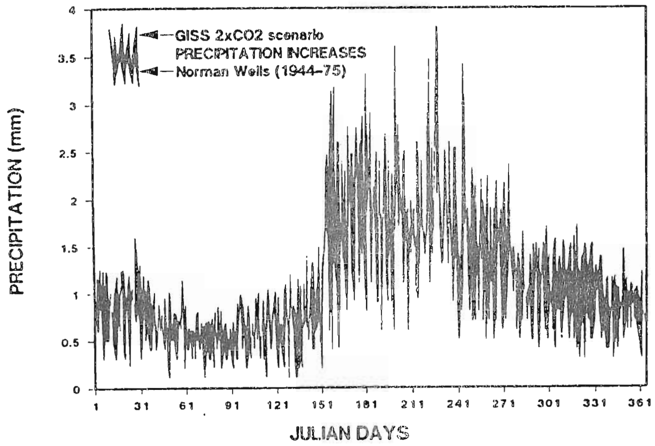


Figure 5.2. Comparison of means, standard deviations, maxima and minima for all calendar days obtained from (**a**) 1944-75 temperature record of Norman Wells and (**b**) 100 years of simulated data based on the GFDL temperature-change calculations due to CO2 doubling. In addition, comparison of observed and simulated mean daily precipitation for all calendar days (**c**), with the shaded zone representing the precipitation increase based on the GISS precipitation-change calculations due to CO2 doubling.

CLIMATIC CHANGE SCENARIOS FOR NORMAN WELLS, CANADA, UNDER CO2 DOUBLING

(WOO 92)

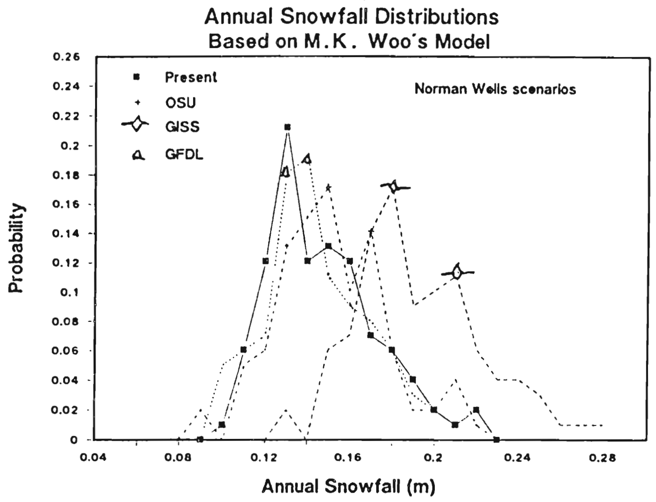


Figure 5.2d

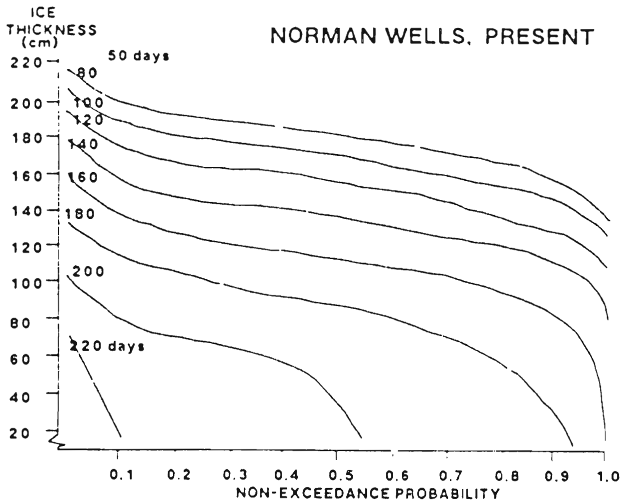


Figure 5.2e

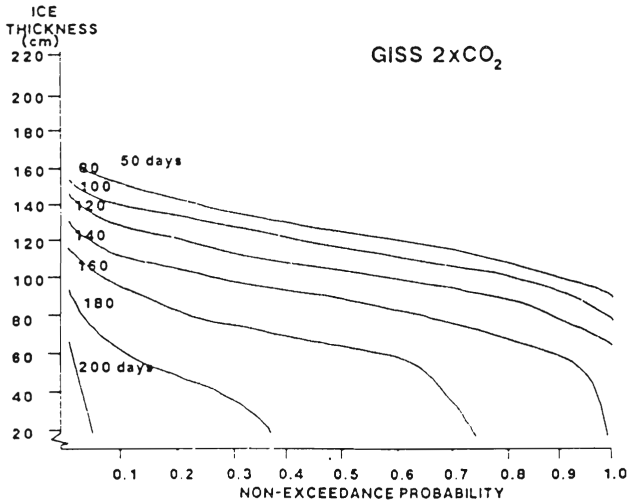


Figure 5.2f

Annual snowfall probabilities simulated for the present day Norman Wells climate and for the climate under CO2 doubling according to three GCMs are presented in **Figure 5.2d.** **Figures 5.2e and f**: probabilities that the river ice cover at Norman Wells of various thickness lasts for at least a certain number of days in a year, under the present-day climate (e) and under a two times CO2 climate (f) as calculated by the GISS GCM.

5.2 Probabilistic statements based on time series representing past climates

Results from a limited amount of studies analysing records of past temperatures indicate that:

1) the trend of a global warming of about 0.5 °C during the last century is more than can be explained by natural, or internal, variability alone,
2) global temperatures may increase substantially under conditions of double CO2, and
3) some regions may be more sensitive to global warming than others resulting in more realisations with respect to the climate under CO2 doubling.

list 5-3

5.2.1 Studies with regression models

The use of statistical models to explain past temperature trends is an alternative to work published in the early eighties by Hansen et al. (81) and Gilliland (82). They used simple climate models based on physics to determine in a consistent manner the relative importance of various assumed external forcings in producing the observed temperature record. Given basic forcing functions for CO_2, volcanic aerosols and the solar cycles, the variance between the observed temperature record and the temperature trend generated by integrating the climate models has been minimized by adjusting representative forcing parameters. Results of both studies are presented in Figure 5.3. Because these results have not been presented in a probabilistic form, they will not be considered in the further course of this study.

Tol and De Vos uses various statistical models which can be considered of extreme simplifications of reality. They consider only one climatic variable: the annual global mean surface air temperature. The explanatory part of their models are carefully chosen simple models with the cumulative atmospheric concentration of all greenhouse gases (expressed by means of carbon dioxide equivalents) as main component. Next to this deterministic part, a part of the temperature record is explained by a stochastic time series model. So, each of their models is a combination of a deterministic and a stochastic model. Fitting of the model to the data provides estimates of the parameters and their confidence; combined with tests of the statistical adequacy of the description, this results in justified probabilistic statements on the parameters, especially on the one of the greenhouse effect.

In their preferred model (1), the global mean temperature GMT of a certain year t is explained from the solar, volcanic and El Niño influences to capture part of the short term variability, the global mean temperature of the year before (i.e. auto-correlation) to incorporate the influence of the enhanced greenhouse effect, a linear time trend, 0.5513 t, to take the unexplained long term natural variability into account, and white Gaussian noise u_t. In addition, the temperature is sensitive to ENSO activity in the year under consideration, to the solar activity, ENSO and volcanic activity of the year before, and to the volcanic activity of two years earlier.

In the following, mathematical description of this model, SSN denotes sunspot number -the number of sunspots gives a measure for the strength of irradiance of solar energy at the top of the atmosphere. DVI denotes dust veil index: the dust veil index gives a measure for the amount of dust -from volcanic eruptions or else- in the atmosphere which has a mitigating effect on the amount of solar energy reaching the Earth's surface. ENSO gives a measure for the activity of the El Niño-Southern Oscillation phenomenon (for a short description of this phenomenon, see page 49). CO2:EQ is a transformed carbon dioxide-equivalents record: in reaction to a one time increase in atmospheric greenhouse gases, temperature is assumed to converge steadily to its new equilibrium in about 50 years.

$$\begin{aligned} GMT_t = \; & - 1.6206 + 0.4623\, GMT_{t-1} + 0.4204\, SSN_{t-1} - 0.0625\, ENSO_t \\ & - 0.0313\, ENSO_{t-1} - 0.0465\, DVI_t - 0.1226\, DVI_{t-1} - 0.1011\, DVI_{t-2} \\ & + 0.0091\, (1 - 0.4623)\, CO_{2:EQ} + 0.5513\, t + u_t \qquad (5.1) \end{aligned}$$

Model (5.1) is used to reproduce the global mean temperature from 1870 to 1991. The period 1870-1940 ('hindcasts') is used to estimate the parameters of the model; the period 1941-1991 ('forecasts') is used for model validation. Values for the volcanic, solar and El Niño activities, and for the greenhouse gas concentrations are obtained from observations.

Notable results from the work of Tol and De Vos include results from other but similar regression models. Note that the results presented here are all conditional on the preferred model. Results are as follows:

The influence of the rising concentrations of greenhouse gases on the global mean temperature is significant at the 1% level, i.e. the hypothesis that the enhanced greenhouse effect, represented by the atmospheric concentration of carbon dioxide, did not influence the global mean surface air temperature during the period 1883-1990 is rejected with 99% confidence.

The period of 1940-1975, in which the global mean temperature stabilised despite the than current and on-going increase in greenhouse gas concentrations, is described and predicted by the model. According to the model, this is largely due to the influence of El Niño-Southern Oscillation.

The influence of sunspots, or the length of the solar cycle, on the global mean temperature is also studied: it is rather small and not likely to be responsible for the observed temperature rise.

Of the explained natural variability, which amounts to 46% of the total natural variability, 72% can be ascribed to the Southern Oscillation, 20% to the volcanic activity and 8% to the influence of the sun.

The equilibrium temperature reaction to a doubling of the atmospheric concentration of greenhouse gases is 2.8 °C with a standard deviation of 0.8 °C.

For a CO2 rise of 300 ppm, the resulting 95% confidence interval of the forecast ranges from 2.99 °C to 7.02 °C.

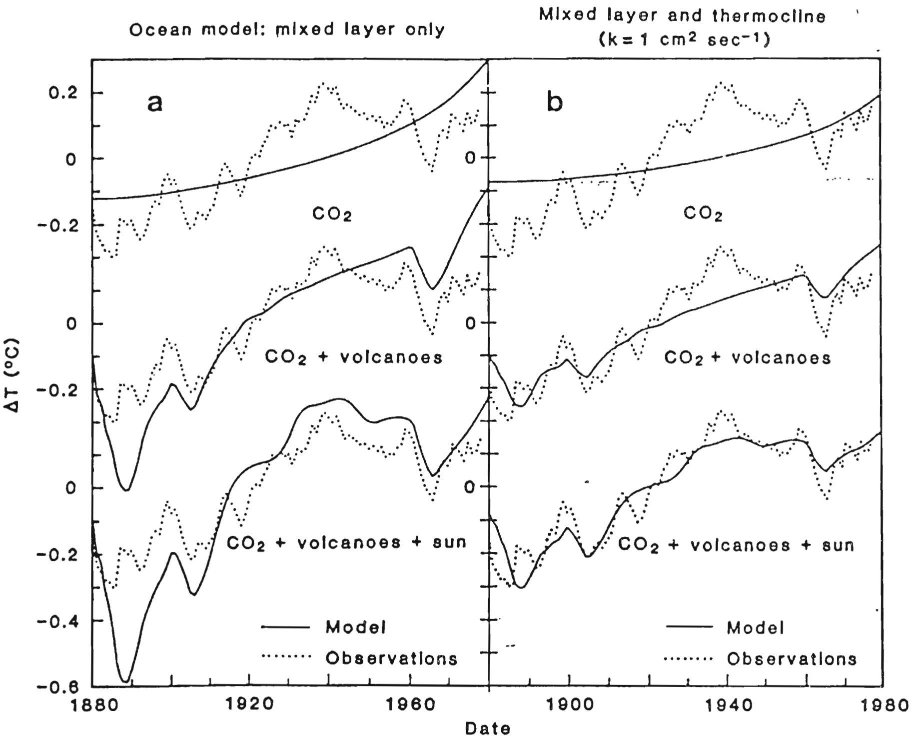


Figure 5.3a. Global temperature trend obtained from a climate model with a sensitivity of 2.8 °C for doubled CO2. The results in (a) are based on a 100-m mixed-layer ocean for heat capacity; those in (b) include diffusion of heat into the thermocline of 1000 m (Hansen et al. 81).

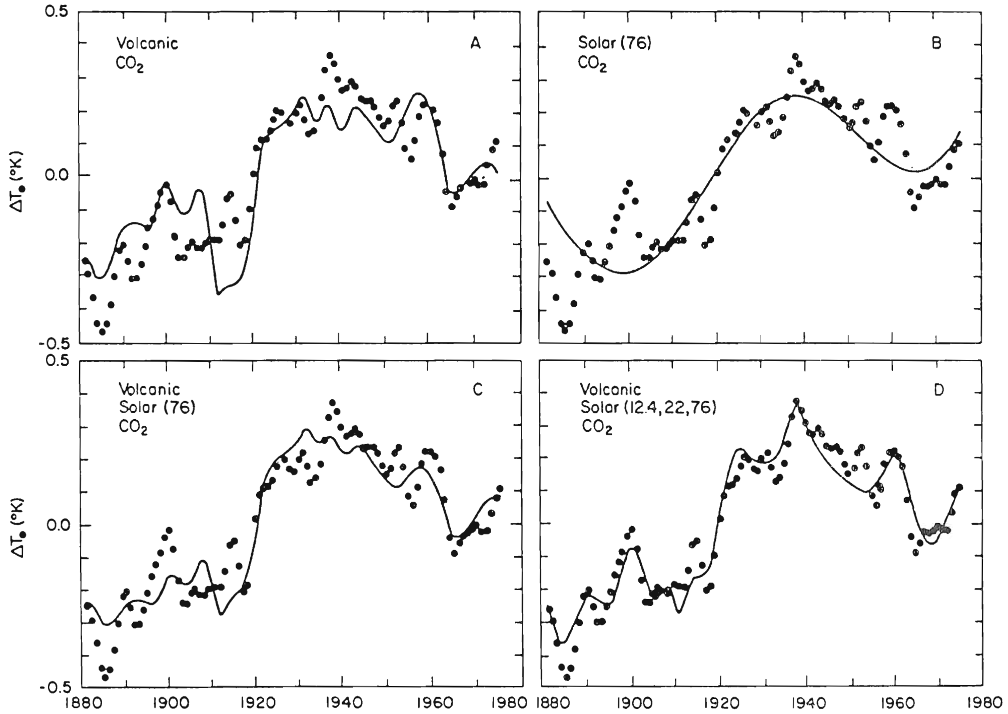


Figure 5.3b. Climate models (solid curve) with various assumed external forcings fitting the observed Northern Hemispheric temperature record. The observational record (●) has been smoothed (Gilliland 82).

FITTING THE RECORD OF OBSERVED TEMPERATURES WITH A REGRESSION MODEL

(TOL 94)

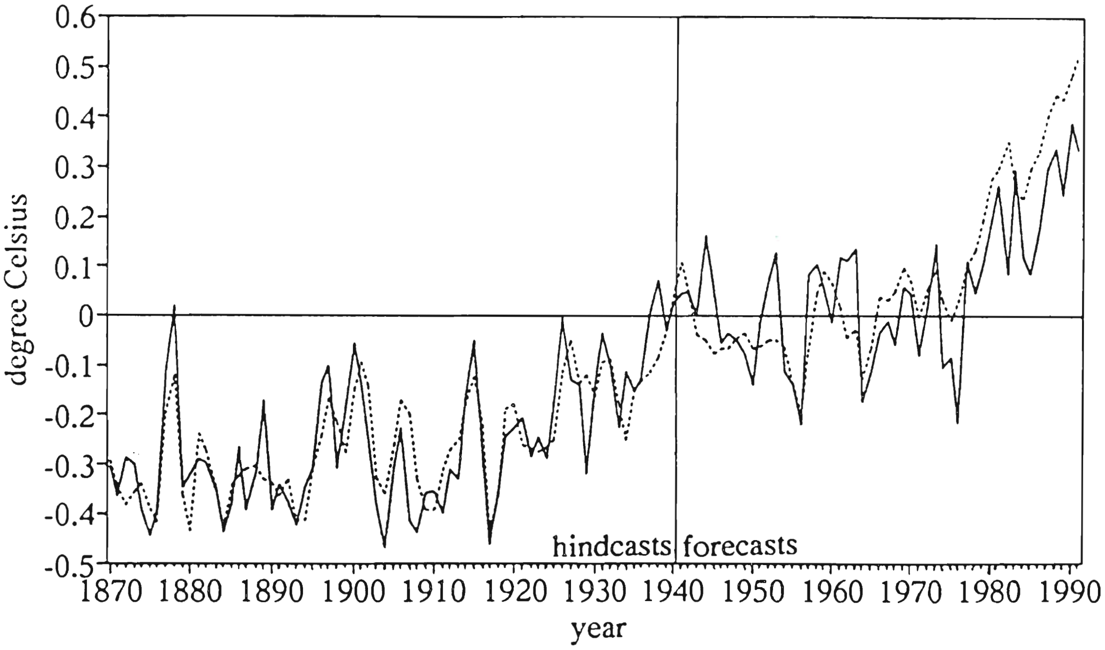


Figure 5.4a. The annual global mean surface air temperature as observed (solid line) and modelled (dotted line) for the period 1870-1991. The period 1870-1940 ('hindcasts') is used to estimate the parameters of model (5.1), without trend. The period 1941-1991 ('forecasts') is used for model validation: the parameters are as estimated for 1870-1940; the observed volcanic, solar and ENSO activity and the observed atmospheric concentrations of greenhouse gases are used. The observed temperature record is presented as deviation from its respective 1950-1979 mean (this also counts for Figure 5.4b).

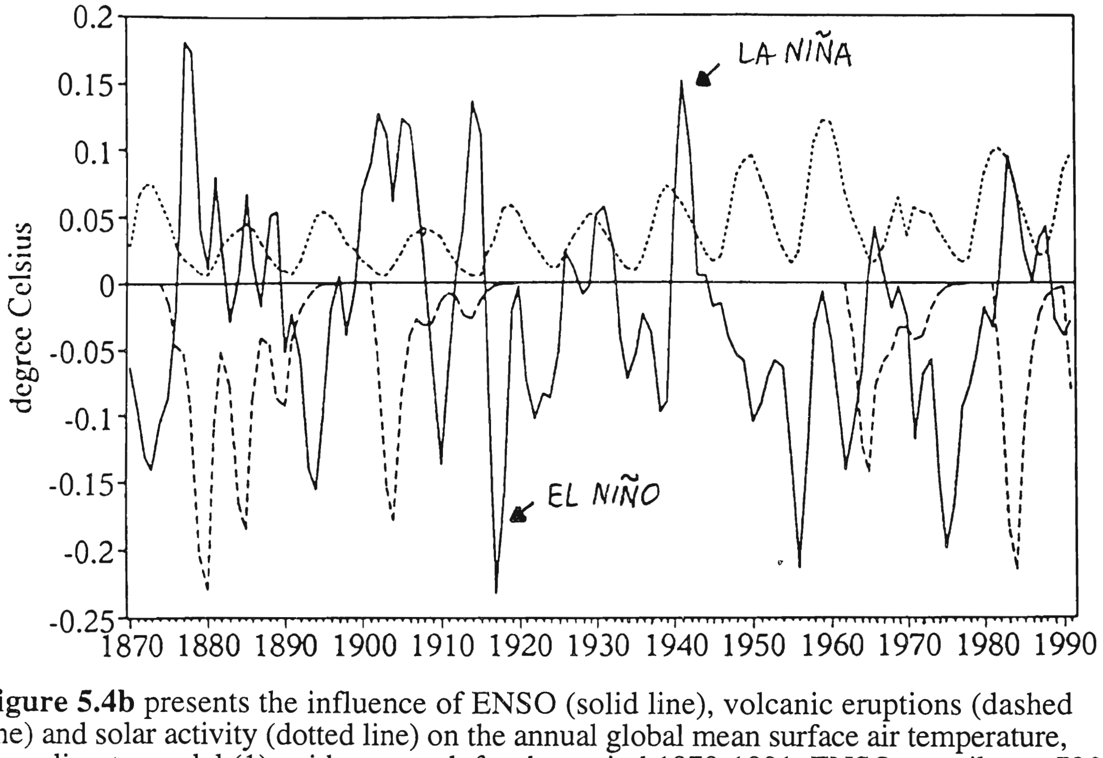


Figure 5.4b presents the influence of ENSO (solid line), volcanic eruptions (dashed line) and solar activity (dotted line) on the annual global mean surface air temperature, according to model (1), without trend, for the period 1870-1991. ENSO contributes 72% to the variability of the composite record, DVI 20% and SSN 8%.

A similiar approach to Tol and De Vos is followed by Schönwiese (86, 91 and 92), and by Schönwiese and Stähler (91). For his regression models he uses a simple linear expression in which any temperature time-series is described by the superposition of four alternative forcing parameter time-series for forcing due to volcanic, solar and ENSO activity and for trace-gas concentrations. The model does not account for so-called auto-correlation. Auto-correlation is present when the value of a given variable is not independent of past values for these variables: e.g. a warm year leads to a higher probability that the next year will also be warm.
The 'best fit' simulations imply phase shifts of the temperature signals in respect to the forcing parameters of 5 years in the case of volcanic forcing and 20 years in case of the greenhouse forcing. The model can be used to calculate the seasonal-meridional patterns of the 'industrial' CO2 forced signals from similar patterns of temperature trends derived from existing temperature records. In addition, a linear extrapolation to a CO2 doubling leads to a statistically derived temperature signal of 3.1 +/- 0.6 °C.
The model is also used to assess the CO2 component of the temperature trend from 1781-1980; according to the model the 'industrial' CO2 increase reveals a Northern Hemisphere temperature increase near surface of 0.7 +/- 0.1 °C (average and standard deviation of all statistical regression runs), statistically significant at the 95% level. By mathematical means a stratospheric cooling trend in recent time which would coincide with the CO2 climate impact thesis may be existent but is non-significant compared with the background variability. Similarly, the SST data do not allow to evaluate a significant CO2 signal to noise ratio. In contrast to that the observed long-term global mean sea level increase (9.3 cm rise in the period 1881-1980) can be predominantly, i.e. 70-80% of variance, attributed to the CO2 effect, i.e. the signal to noise ratios are greater than one even in the case of the 99.9% level.

5.2.2 A study based on the group-analogue method

The group-analogue forecast method is used by Gruza and Rankova (91) to predict temperature changes due to CO2 increases over relatively short periods of 10, 15 and 20 years. Their method makes use of analogue groups in an instrumental temperature record dating back to 1880 and a single predictor, i.e., the CO2 concentration. By doing this, climate fluctuations, related to all non-CO2 factors of both natural and anthropogenic origin, are taken into account statistically. The variability of these fluctuations within the analogue group, i.e. time periods with pratically the same changes of CO2 concentration, gives the opportunity to formulate the forecast in a probabilistic form. Neglecting the dependence on the climate system inertia, they show the total temperature variation during the period t as the sum of two terms:

$$\begin{aligned}\Delta T(t) &= \Delta T_{\text{anthropogenic factors}}(t) + \Delta T_{\text{non-anthropogenic factors}}(t)\\ &= f\,(\Delta C_t / C) + (\text{non-anthropogenic factors})_t\end{aligned}$$

where the first term presents temperature growth due to man-induced change in the CO2 concentration and the second one shows the temperature variation due to all other factors not considered separately. ΔC_t is the CO2 concentration change in the period t. There is reason to believe that all the periods in instrumental observations of the CO2 concentration series characterized by identical or almost identical, i.e. analogous, relative CO2 concentration changes will correspond to identical or analogous man-induced temperature changes. Statistical characteristics of such an analogue sample, i.e., conditional distribution of climatic indicators (global surface air temperature), will comprise probability climate forecast. It will also be the probability forecast of real climate taking into account anthropogenic climate changes unlike the forecast of anthropogenic climate changes proper. Only a mean or a median value of such a distribution will to some extent characterize the signal, i.e. the global temperature variations due to CO2 increase. Variability features will characterize real climate changes with man-induced changes being the same.

The suggested method differs advantageously from the extrapolation by means of regression, because it does not use any hypotheses of the nature of statistical relations and distribution functions. They only relied on the hypothesis that similar reasons lead to similar consequences.

The results of this study are given in the Tables 5.1 and 5.2 and in Figure 5.5. Table 5.1 presents the characteristics of the analogue groups for which they used the periods with similar relative changes of the CO2 concentrations. It is obvious that the periods with the corresponding relative changes in the concentrations in the past were longer than the forecast lead time. That means that ignoring the dependence on the climate system inertia, they have obtained positively biased values of temperature variations, because they had previously assigned the variations which took place during longer periods to shorter ones.

According to Table 5.2 in 2000-2005 a more significant temperature increase may take place compared to that in 1995-2000. The possibility that the Northern Hemisphere will cool during the three considered periods cannot be excluded.

The dashed line in Figure 5.5 shows the course of the forecasted median, i.e. the value below and above which the 5-year mean surface air temperature can be with a probability. of 50%. Besides, dotted curves show the 25 and 75% percentiles. Thus, the interval between the dotted curves corresponds to the 50% confidence intervals of predicted values of the 5-year mean temperatures. That is, in half of the cases the 5-year mean temperature can be expected to be within the given interval. With 50% probability the 5-year mean will be above or below the dotted line.

Disadvantage of this method is that it is practically impossible to prepare climate forecasts with regard to anthropogenic CO2 increase for the periods more than 20 years with the help of this method because of insufficient analogue periods in data series for the last several centuries.

5.2.3 A study based on the palaeo-analogue method

Shabalova and Können (95) regarded the change in greenhouse gas concentrations as a main mechanism for climatic change in Mid-Pliocene (~3-4 Myr BP; global warming ~4 °C) and a significant climate forcing in Eemian (~125 kyr BP; ~ 2 °C) and Mid-Holocene (~5-6 kyr BP; ~1 °C). Consequently, each of the three warm periods may be considered as an approximate equilibrium analogue for the future climate. But if the periods are taken together, the data indicate the existence of regions with good and poor agreement between the different epochs (Figure 5.6a and b). They supposed that the regions with good agreement (small divergence in palaeo data) present the typical structure of regional equilibrium warming, while poor agreement (large divergence) indicated the regions which are sensitive to the difference in analogues. Reasons for this could be either a difference in sea-ice boundary conditions in past epochs or a difference in oceanic circulation.

The authors note that prior to use palaeo data as a scenario for the regional distribution of temperature in a future climate, two assumptions should be tested. The first is that the regional anomaly patterns produced by global warming are in first approximation independent of the cause of the warming. The second assumption is that the regional structure which follows from this method is a structure which applies to climatic change in a situation of equilibrium. It is not clear whether this structure will also appear in the current situation which is a transient one. Regarding the context of this study, it should be noted that the palaeo-analogue method is used here in the form of a sensitivity study not aimed at providing quantitative probabilistic results. Because of this, the results of the palaeo-analogue method will not be discussed in the remainder of this study.

EXTENDING THE RECORD OF OBSERVED TEMPERATURES WITH THE GROUP-ANALOGUE METHOD

(GRUZA AND RANKOVA,91)

Table 5.1

Characteristics of analog groups (periods with analogous CO_2 concentrations)

Characteristics	Forecast period/lead time		
	1995/10 years	2000/15 years	2005/20 years
Expected relative change (%) of CO_2 concentration compared to 1985	5.78	8.67	11.56
Number of analog	20	20	19
Duration (number of years) of period-analogue:			
minimum	15	25	41
maximum	36	70	90
Relative change (%) of CO_2 concentration during period-analogue:			
mean	5.80	8.68	11.47
minimum	5.72	8.34	10.62
maximum	5.90	8.81	11.61

Table 5.2

Forecasting estimates of expected variations of 5-year mean air temperature (°C) for analog groups

Region	Characteristics of analog groups	Period of the forecast/lead time		
		1995/10 yrs	2000/15 yrs	2005/20 yrs
Northern Hemisphere	Median	−0.03	0.06	0.23
	Mean	−0.01	0.07	0.23
	Norm	0.20	0.12	0.12
	Minimum	−0.33	−0.16	−0.02
	Maximum	0.31	0.25	0.44

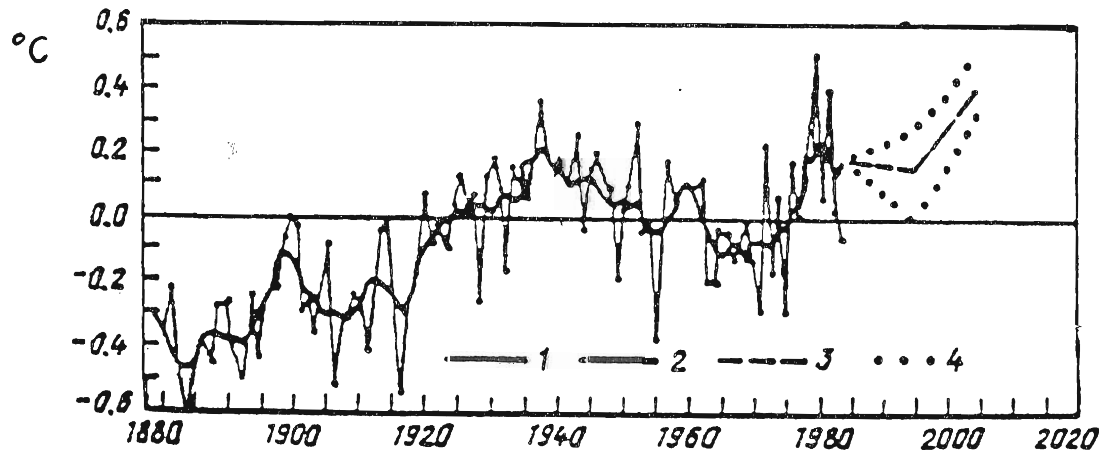


Figure 5.5. Time series and probability forecast of Northern Hemispheric surface air temperature anomalies for 1995-2005. Base period for calculating anomalies 1951-1980. Starting year for the forecast 1985. 1) annual mean temperatures; 2) running 5-year mean temperatures; 3) forecasting median; 4) 25 and 75% percentiles indicating the 50% confidence interval of the probability forecast.

CALCULATING THE SENSITIVITIES OF REGIONAL CLIMATES TO A GLOBAL CLIMATIC CHANGE WITH THE PALAEO-ANALOGUE METHOD

(SHABALOVA AND KÖNNEN, 95)

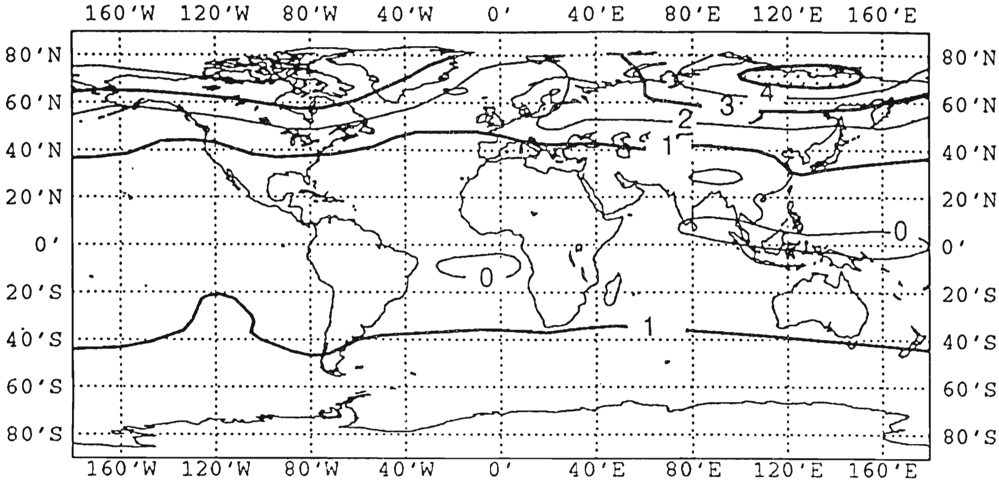


Figure 5.6a. Scaled winter temperature increase *t* in °C as deduced from palaeoclimatologic data of three warm climates. For one degree of Northern Hemispheric winter warming, the isolines of *t* represent the local response *dT* in centigrades. Contour intervals are 1 °C. Areas where *dT* is larger than 5 °C are stippled.

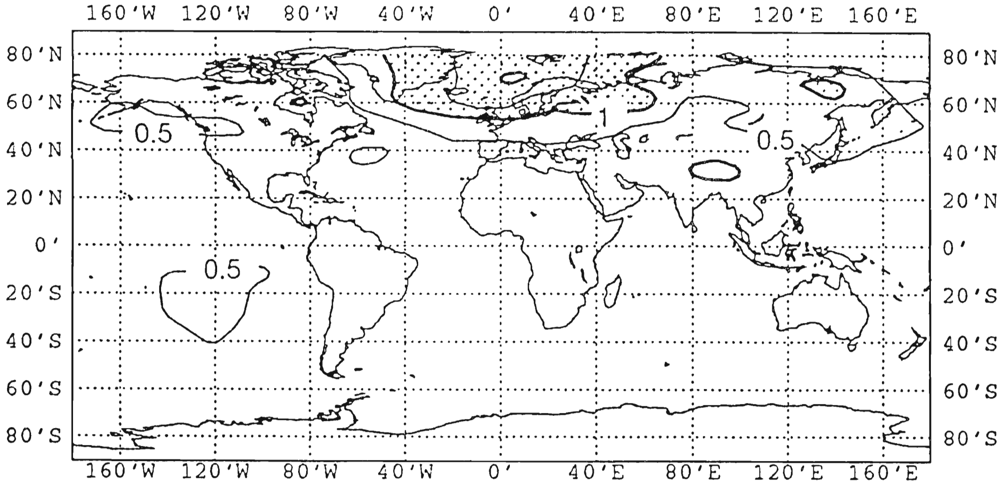


Figure 5.6b. Scaled mean deviation *r* of the winter temperature increase (see above). Contour intervals are 0.5 °C. Areas where the deviation *r* is larger than 1 °C are stippled.

5.3 Probabilistic statements based on expert opinion

Opinions from experts in the field of the atmospheric sciences make clear that:

1) it is very probable that climate will change significantly, and
2) some experts would like to bet for large sums of money on a fifty-fifty basis with people who do not believe that the predicted warming rate for the next decades will be lower than the range as by the atmospheric community accepted.

list 5-4

5.3.1 A survey of expert opinion

Statements with respect to climatic change based on expert opinion can be found in a report by the Department of Defence (78). The underlying purpose of the study was to define and estimate the likelihood of changes in climate during the period 1970-2000, and to construct climate scenarios for the year 2000. Information was collected from a carefully selected group of 28 experts through the use of a structured questionnaire. 24 returned the questionnaire. Of these, 21 contained quantitative information which was asked for in the questionnaire. Ten separate questions dealt with particular climatic variables and/or specific geographic regions of interest.

Most respondents, as well as some of the invited panelists who declined to participate, voiced some degree of apprehension or concern about the questionnaire and the use (and possible abuse) of the information derived from their responses. These concerns centered on the following issues:

I) the lack of sufficient actuarial experience, comprehensive theories, or adequate models to support the quantitative esimates given in the questions;
II) the possible suppression of the full range of uncertainty accompanying the responses; and
III) the risk of being an unwitting party to 'science by consensus'.

In the preparation of the report, the project team has given considerable attention to these concerns in analyzing the data and aggregating the range of views -and the expressed qualifications- provided by the respondents. Realizing that confident predictions of climate are beyond the state of the art, the project team has proceeded on the assumption that expert probabilistic judgments, properly qualified, constitute the best available guidance for those who must make policy in matters affected by climate.

Probabilistic results were deduced from answers on questions on the following ten topics: average global temperature, average latitidinal temperature, carbon dioxide and turbidity, precipitation change, precipitation variability, mid-latitude drought, outlook for 1977 crop year, Asian monsoons, Sahel drought, and length of the growing season.

Each question elicited information about three elements: probabilistic forecasts on a particular climatic variable, reasons for quantitative estimates, and self and peer estimate rating.

SELF AND PEER RATING

Using the self-ranking definitions provided in the instructions, please indicate your level of substantive expertise on this major question.

5 - 4 - 3 - 2 - 1

Again using the self-ranking guide, please identify those other respondents whom you would rate as "expert (5)" or "quite familiar (4)" in their answer to this particular question.

(5) EXPERT—You should consider yourself an *expert* if you belong to that small community of people who currently study, work on, and dedicate themselves to the subject matter. Typically, you know who else works in this area; you know the US and probably the foreign literature; you attend conferences and seminars on the subject, sometimes reading a paper and sometimes chairing the sessions; you are most likely to have written up and/or published the results of your work. If the National Science Foundation, National Academy of Sciences, or a similar organization were to convene a seminar on this subject, you would expect to be invited, or, in your opinion, you should be invited. Other experts in this field may disagree with your views but invariably respect your judgment; comments such as "this is an excellent person on this subject" would be typical when inquiring about you.

(4) QUITE FAMILIAR—You are *quite familiar* with the subject matter either if you were an expert some time ago but feel somewhat rusty now because other assignments have intervened (even though, because of the previous interest, you have kept reasonably abreast of current developments in the field); or if you are in the process of becoming an expert but still have some way to go to achieve mastery of the subject; or if your concern is with integrating detailed developments in the area, thus trading breadth of understanding for depth of specialization.

(3) FAMILIAR—You are *familiar* with the subject matter if you know most of the arguments advanced for and against some of the controversial issues surrounding this subject, have read a substantial amount about it, and have formed some opinion about it. However, if someone tried to pin you down and have you explain the subject in more depth, you would soon have to admit that your knowledge is inadequate to do so.

(2) CASUALLY ACQUAINTED—You are *casually acquainted* with the subject matter if you at least know what the issue is about, have read something on the subject, and/or have heard a debate about it on either a major TV or radio network or an educational channel.

(1) UNFAMILIAR—You are *unfamiliar* with the subject matter if the mention of it encounters a veritable blank in your memory or if you have heard of the subject, yet are unable to say anything meaningful about it.

Figure 5.7a. An excerpt of the instructions provided at the end of each question of the questionnaire and designed to assess the respondents' expertise, including the guidance provided for self-ranking expertise, is given.

CONVERSION OF EXPERTISE RANKING TO WEIGHTED SCALE

Expertise	Weight
Expert	4
Quite familiar	2
Familiar	1

Table 5.3. A simple averaging of self and peer ratings for each respondent on each question provided a weighing that was subsequently used in aggregating responses. The particular weighing scale that was used is shown.

I. GLOBAL TEMPERATURES

Shown below is a historical record of changes in the annual mean temperature during the past century for the latitude band, 0-80°N.

CHANGE (°C) IN ANNUAL MEAN TEMPERATURE, 0-80 °N. LATITUDE

Source: Mitchell, NOAA

On the graph shown above, indicate your estimate of the general future course of the change in mean annual temperature (for 0-80° N.Lat.) to the year 2000 by:

- drawing a temperature change path to the year 2000 so that you estimate only 1 chance in 10 that the path could be even lower
- drawing a change path to the year 2000 so that you estimate an even chance that the path could be either lower or higher
- drawing a change path to the year 2000 so that you estimate 1 chance in 10 that the path could be higher

Figure 5.7b. Question I of the questionnaire is reproduced. This question, dealing with possible changes in global mean temperature (for the figure, the period 1880-84 has been used as the zero reference base), was considered a pivotal question because perceptions of global mean temperature greatly influence perceptions with respect to the climate variables treated in subsequent questions.

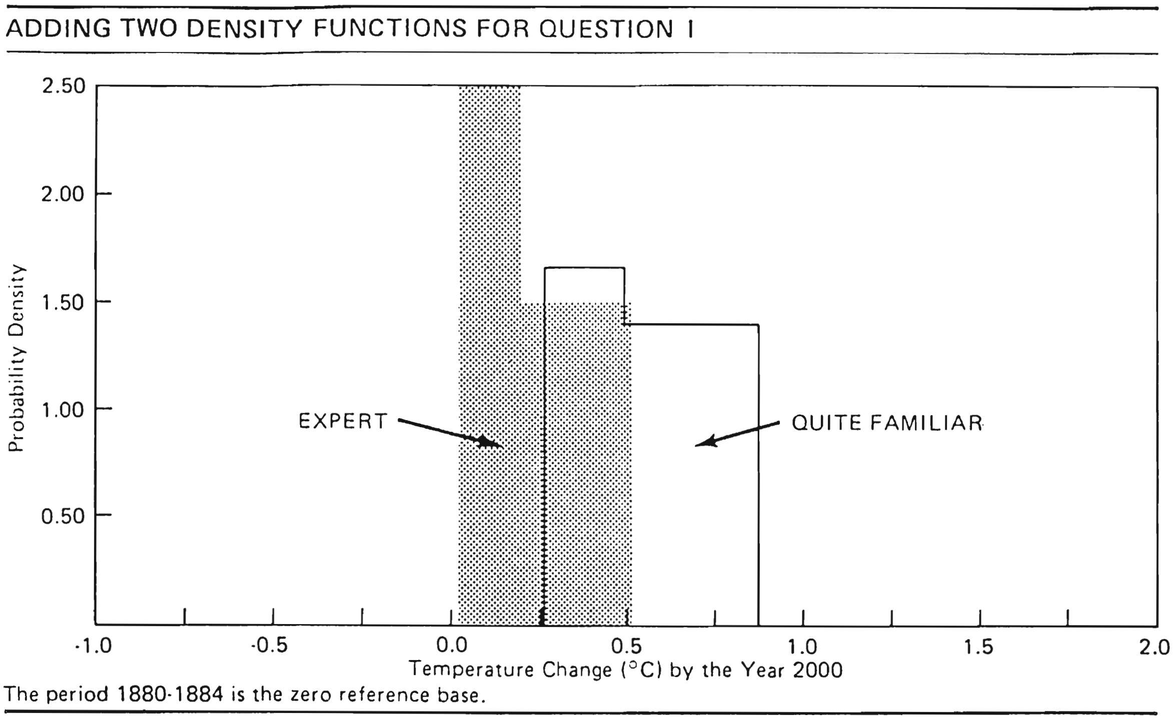


Figure 5.7c. The processing of responses to question I is illustrated using the answers to this question by two respondents.Unweighed density functions from each of two respondents are shown. The functions are weighed by the appropriate expertise weights (Table 5.3), added and then divided by the sum of the weights to obtain the combined and normalized density function. The area under the curve of this function, shown in Figure 5.7d, is equal to unity.

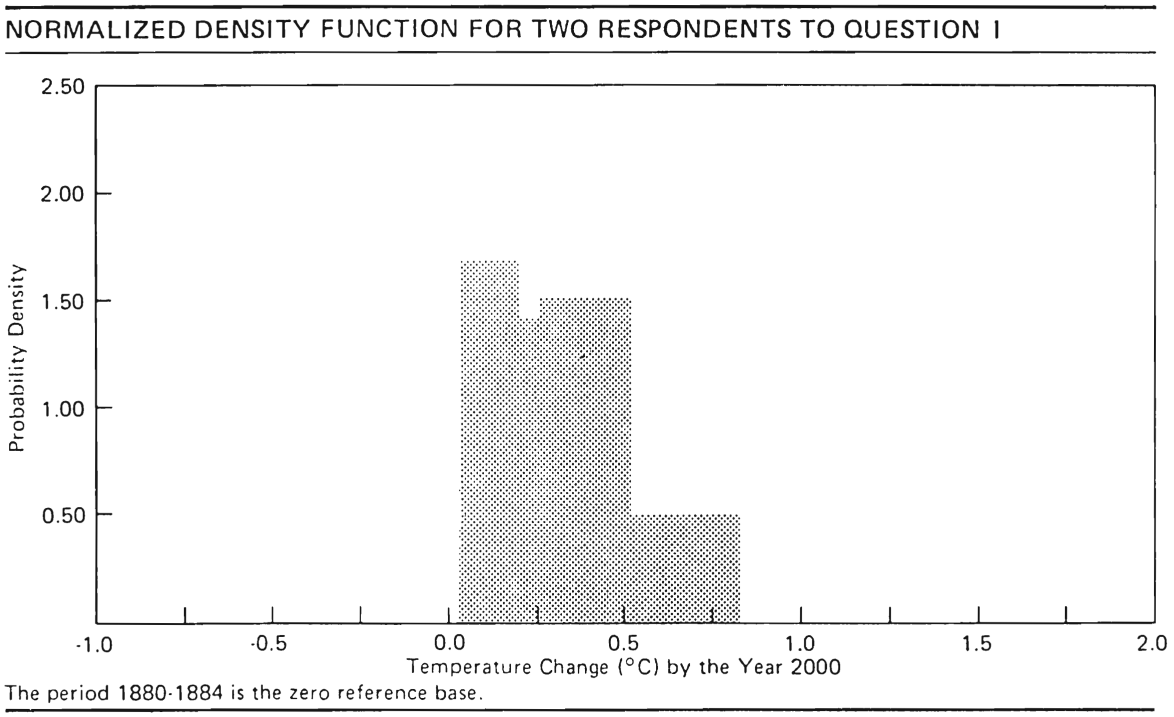
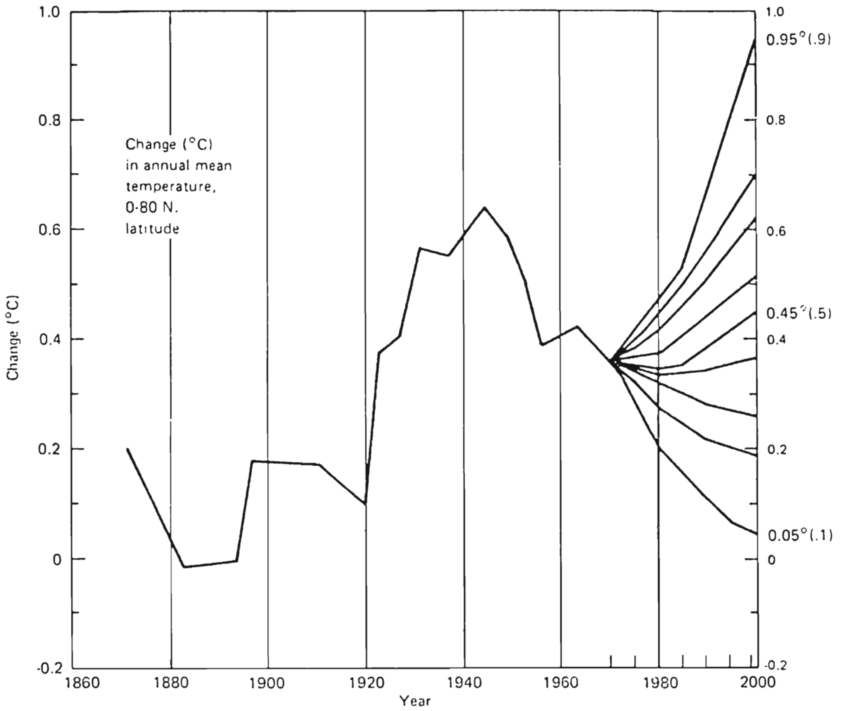


Figure 5.7d.

PROBABILITY OF MEAN NORTHERN HEMISPHERE TEMPERATURE CHANGE
TO THE YEAR 2000 AS DETERMINED BY THE PANEL OF CLIMATIC EXPERTS



The period 1880-1884 is the zero reference base.

The procedure outlined above is repeated for the responses of each of the other panelists. **Figure 5.7e** is a plot of the aggregated normalized responses of the full panel for the year 2000. The information contained in the probability density functions is shown in Figure 5.7f as extensions to the original curve. The extensions on the curve show the 10th, 50th and 90th percentiles for each year from the then present to the year 2000. Intermediate percentiles are also plotted.

PROBABILITY OF MEAN NORTHERN HEMISPHERE TEMPERATURE CHANGE
BY THE YEAR 2000 AS DETERMINED BY THE PANEL OF CLIMATIC EXPERTS

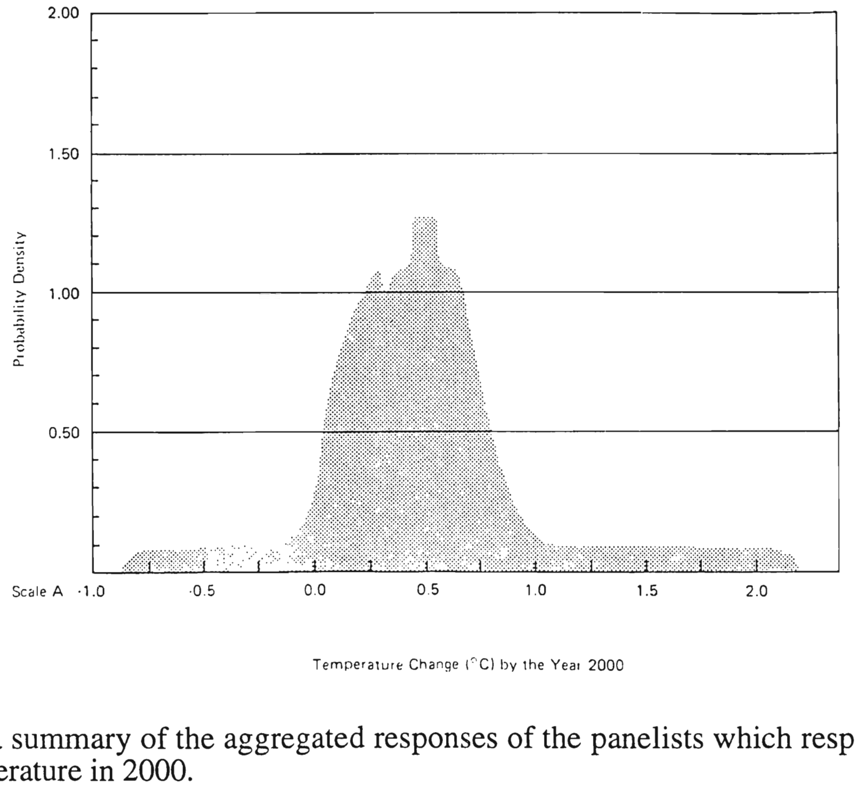


Figure 5.7f is a summary of the aggregated responses of the panelists which respect to the global temperature in 2000.

5.3.2 The opinion of individual experts

Jerry Mahlman, director of Geophysical Fluid Dynamics Laboratory of Princeton University, one of the few institutes which are in the possession of a coupled GCM, is a climatologist who presented quantitative probabilistic statements about climate change before an audience of state authorities (Mahlman 93). Quotations follow from a congressional hearing before the committee on energy and natural resources:
"I will give my estimates of current scientific confidence based upon simple betting odds. When I say virtually certain, I mean there is no plausible alternative to what we see. Very probable means that I estimate about a 9 out of 10 chance that the predicted effect will happen within the range predicted. Probable implies about a 2 out of 3 chance. When I say uncertain, I mean a plausible effect but which lacks appropriate scientific evidence."
"Human-caused increases in greenhouse gases: virtually certain; radiative effect of increased greenhouse gases: virtually certain; large stratospheric cooling: virtually certain; long time-scales in the problem: virtually certain; global-mean surface warming: 9 out of 10; global-mean precipitation increase: 9 out of 10; reduction of northern sea-ice: 9 out of 10; northern polar winter surface warming: 9 out of 10; rise in global-mean sea level: 9 out of 10; higher-latitude precipitation increase: 2 out of 3; summer mid-continental dryness and warming: 2 out of 3; regional vegetation changes: uncertain; tropical storm increases: uncertain; regional and temporal details of climate change in the next 25 years: uncertain."

Mahlman (91) has published subjective probabilistic statements about future climatic change also. The passages which contain these statements follow.
"In the deliberately wimpy language of science, individually these phenomena (signals which can be considered as "early-warnings", WF) are "not inconsistent" with a hypothesis that the greenhouse effect is already underway. Together, they make a rather respectable case. Do they collectively provide the elusive Smoking Gun? My own opinion is, if this were a civil-court case, the preponderance of the evidence would indicate a vote of YES. If it were a criminal case, could we vote for a conviction that is beyond a reasonable doubt? I can visualize a hung jury with a vote of 10 YES and 2 NO."
"I have been on record for over 4 years arguing that the "betting odds" are about 9 out of 10 that the global-mean surface temperature will increase within the range 1.0-4.5 °C by the middle of next century. Does the reader think it is even money that the warming wont happen or it will be less than 1.0 °C? If so, I have a spare $1000.00 I would be delighted to invest with you in a mutual business transaction."

Another eminent climatologist is James Hansen. In april 1990 Hansen told a group of climatologists that his confidence that the greenhouse effect had arrived was even higher than it was in 1988, when he testified before Congress that he believed the global warming of recent decades was driven by gases produced by human activity (Hansen 90). So sure was Hansen at that time of this conclusion that he said he'd bet even money that one of the next three years will be the hottest in 100 years. "People aren't going to believe such an 'incredible' and 'scientifically outrageous' prediction", Hansen said....

CHAPTER 6

Case study: a probabilistic result based on modelled wisdom, added wisdom and added ignorance

This chapter starts with the observation that processing of model results may lead to probabilistic statements. For this, a new method is proposed. This method takes into account knowledge which has not yet been incorporated by the coupled climate models as well. In addition ignorance of many processes is given a quantification. Thus, several forms of information are used. The result is a probabilistic prediction for the change in temperature in 2060 with respect to the situation in 1990. This prediction is done for the world as a whole and for the average situation in Western Europe. With this newly developed method it is calculated that:

1) temperatures will have changed by between +0.9 and +2.9 °C (world) and by between +0.6 and +3.8 °C (Europe) with 95% confidence if output from four coupled models is used only,
2) temperatures will have changed by between -0.2 and +3.8 °C (world) and by between -0.7 and +4.9 °C (Europe) with 95% confidence if a correction is made to the model results for processes which do influence climate but which acknowledgely have not yet been accounted for by the models,
3) temperatures will have changed by between -1.0 and +4.6 °C (world) and by between -2.3 and +6.5 °C (Europe) with 95% confidence if an additional correction is made for surprises which, by their nature, cannot ever be predicted and if uncertainties due to the inadequacy of the model description of sub-grid scale processes are accounted for, and
4) the distribution of the temperature changes as predicted by palaeo-climatic results agrees well with the results obtained from model runs.

It is concluded that the new method is suitable to produce probabilistic statements on the future climate. At the same time it is acknowledged that this method does probably not provide information suited for use in a risk approach when it is used in the way as presented in this chapter.

list 6-1

6.1 Introduction

In this section it is argued that:

1) statistical treatment of model output may lead to probabilistic statements on climatic change,
2) these statements should be corrected for both imperfect modelling and imperfect knowledge, and
3) palaeo-climatic results may be used to test the results obtained for meteorological consistency.

list 6-2

The purpose of this chapter is to put the predicted change of the climate in probabilistic terms by a method which is different from the ones identified in the previous chapter.

Probabilistic statements about the climatic change are obtained when, for instance, the calculated temperature increase is accompanied by a standard deviation. This last term, which is a statistical term and which, thus, should be calculated, represents a range centred on a certain result, here the calculated temperature increase under CO2 doubling. This range indicates what the probability is that the temperature increase will be higher or lower than the calculated value. If we have information about the possible realisations of a system and about the relative occurrences of these realisations, we can calculate a so-called distribution function. If we have no or only very little information about the possible realisations and about their relative occurrences, we cannot. In that case assumptions about the distribution are often made. This applies to the calculations performed in this chapter as well. It is assumed that the future realisations of the climatic system comply with a 'normal' or 'Gaussian' distribution. There is no specific reason why this should be the case or it would have to be the fact that most values presented by different models for climatic variables in the future seem to be distributed 'normally' (Figure 6.1). However, as there is no reason to assume a different distribution and as this distribution is both widely accepted and easy to process, in this chapter a normal distribution is assumed for all climatic variables for which the future sign and magnitude has been calculated.

A minimal introduction to statistical methods, leading to quantifications of standard deviations, will be given in this section before these methods will be applied to the values calculated in the remainder of this chapter in order to give the probability of a well defined climatic change.

The temperature change that will take place the following decades is obtained with help of results from four coupled-General Circulation Models (coupled-GCMs). These are climate models with a coupled representation of atmospheric and oceanic processes. With such models, it is in principle possible to calculate the temperature effect due to a time-dependent increase of the CO2 concentration in the atmosphere; a situation which exists currently and which is expected to remain for the following five decades or so. Unfortunately, the current state-of-the-art-models are not perfect. Many physical processes have not yet been clarified or, if they are, have not been modelled adequately. Consequently, model results are uncertain. In this section an attempt is made to quantify both sources of uncertainty, i.e. absence of some physical mechanisms and inadequate modelling of these mechanisms. Some uncertain factors identified have been quantified in the form of a deviation from the temperature increase, as obtained from averaging the output of four models, and an additional standard deviation associated with this temperature increase. For the calculation of the respective standard deviations normal distributions have been assumed. There is no specific reason to believe that this assumption is realistic, nor is there any reason to assume a specific distribution which is non-normal.

It is the issue to find the largest standard deviations, because these have the largest influence on the final result. Combining all standard deviations found in this way gives the final standard deviation and an adapted value for the temperature change under CO2 doubling. The probability of the climatic change is then given by the temperature and this final standard deviation. This combination of a temperature change and its accompanying standard deviation will be given on three spatial scales; the global scale, the zonal scale, represented by a small zonal band surrounding the 53rd latitude North, and the regional scale represented by, in this case, Western Europe.
The forcing imposed in the model run can be attributed to the predicted gradual increase of the atmospheric CO2 concentration. This increase causes a change in the radiative balance, which represents the net amount and net direction of radiation through the Earth's atmosphere. Some quantitative information will in this study be given about the extent to which processes influencing the point in time at which a doubled CO2 concentration in the atmosphere will be reached, i.e. the timing effect. This effect depends strongly on the emission scenario used.

Some palaeo-climatologic studies have also resulted in predictions about the temperature change in a two times CO2 climate. The model results obtained by the method described above will be compared to these palaeo-climatic results.

6.1.1 Statistical methods used

It is important to give some indication of how close the result is likely to be to the true value. Such indication can be given by the standard deviation. When measurements are made, the individual values will vary. The mean value $\bar{x}$ is normally taken as the best value of the quantity. This $\bar{x}$ will most of the time not be equal to the true value X. The most that can be done is to say that there is a certain probability that X lies within a certain range centred on $\bar{x}$. This range is given by the standard deviation of the distribution, which is a measure of the spread of the distribution. For this study the distribution is given by results from four coupled GCMs. Thus, the distribution contains four values only, the minimum for use of this statistical theory. The mean value for the temperature increase can be calculated easily. The accompanying standard deviation σ which is due to the spread in measurements is given by the following equation:

$$\sigma = \left(\frac{1}{n-1}\sum (x_i - \bar{x})^2\right)^{\frac{1}{2}} \qquad \text{(equation 6-1)}$$

where x_i are the four individual temperature increases as given by the models.

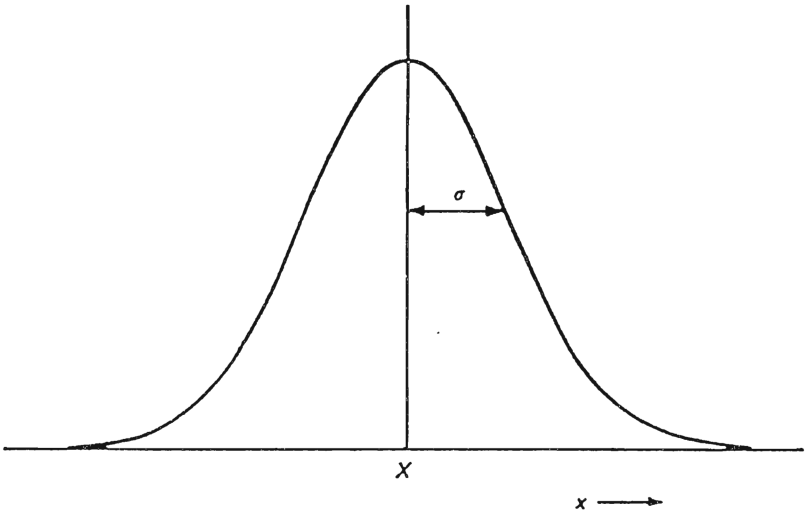


Figure 6.1. A Gaussian distribution function, with points of inflexion at x = $\bar{x} \pm \sigma$.

All individual measurements together form a distribution function. This function gives the fraction of the total number of readings that lie in the interval x+dx. A special distribution function, specified by the two constants X and σ is known as a Gaussian or normal distribution. Its shape is presented in Figure 6.1. Table 6.1 presents the probability that X lies in a specific, well-defined range around $\bar{x}$.

z	Approximate fraction of readings in area of z times σ
0	0
1	0.683
2	0.954
3	0.9973
4	0.99994

Table 6.1. Probability that a reading lies in the range defined by $\bar{x} \pm$ z times σ, for a Gaussian distribution.

Errors

The uncertainties in climate simulations have been quantified in the form of a standard deviation. These standard deviations have been obtained in different manners. Mostly , the sources of uncertainty are treated as being errors. Some theory about such errors will be given below.

When a (physical) quantity is measured, the value obtained will not exactly be equal to the true value. It is important to give some indication of how close the result is likely to be to the true value. This is done by including an estimate of the error in the value. For example, the temperature increase is given as:

$$\Delta T = (1.0 \pm 0.5)\ ^{\circ}\mathrm{C}.$$

By this is meant that it can be expected that the temperature increase to be somewhere in the range between 0.5 and 1.5 °C. The temperature increase is given as a probability statement. This implies that it is not certain that the value lies between the limits quoted, but that there is a certain probability of its doing so. The error represents the best estimate of the standard deviation of the result that would be obtained if the entire experiment were repeated many times.

Errors may be devided into two kinds, systematic and random. A systematic error is one which is constant throughout a set of measurements. In this study the cold-start phenomenon, for example, causes a temperature increase which is systematically too large. A random error is one which varies and which is equally likely to be positive or negative. These errors cause successive readings to spread around the true value of the quantity. An example is given by the emission rate of greenhouse gases. The emission scenarios used in the simulations can be both too high and too low. So the error which is due to this uncertainty may also be too high or too low. Both kind of errors are presented schematically in Figure 6.2.

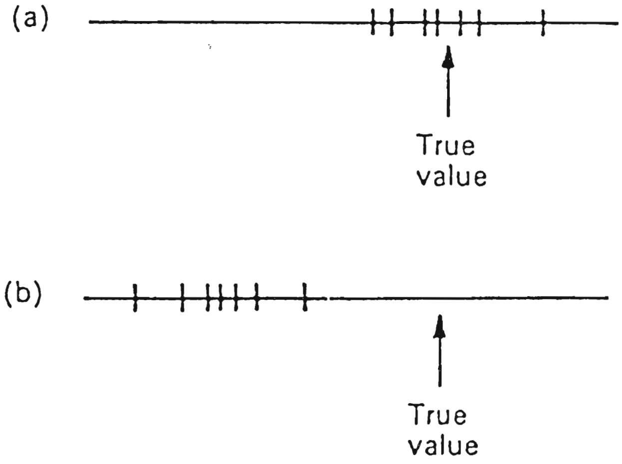


Figure 6.2. Set of measurements (a) with random errors only and (b) with systematic plus random errors. Each point indicates the results of a measurement.

The compounded standard deviation

The standard deviations which will be attributed to the most likely temperature change in 2050 due to various uncertain processes and which all have been obtained in an individual manner, have to be compounded in order to give a standard deviation which represents all sources of uncertainty. This will be done in the following manner:

$$\sigma = (\sum \sigma_i^2)^{\frac{1}{2}} \qquad \text{(equation 6.2)}$$

where σ_i presents all individual obtained standard deviations. The equation may only be used when all individual values of the standard deviation are independent.

6.2 Modelled wisdom; the state-of-the-art in the atmospheric sciences

The four coupled models used for this study:

1) have each other features making it difficult to compare their output in a direct way,
2) agree generally well in the qualitative description of the temperature change for the globe as a whole as well as for the North Atlantic, and
3) produce each a similar quantitative sensitivity for the temperature change in Western Europe with respect to the global temperature change as calculated by the same model.

list 6-3

For this study the temperature increase in a two times CO2 climate has been obtained from the results of simulations with general circulation models (GCMs) with a coupled representation of the atmosphere and the ocean. The enormous amount of computer resources required for these experiments has limited the number of institutions which have performed such integrations to four (see Table 6.2). Shortly, the difference between these coupled models and models which only represent the atmosphere or the ocean will be described. Why only the results of coupled models will be used will be discussed also. Remarkable conclusions will be given special attention.

Why Coupled Ocean-Atmosphere models?

GCMs in which no coupling is established between atmosphere and ocean cannot simulate a gradual increase of the atmospheric CO_2 concentration. In experiments with those models the equilibrium is generally calculated after an abrupt change in the radiative forcing is imposed. When an atmospheric model has also disposal of a detailed and highly developed ocean, the climate change is simulated more realistically. The retardation effect of the ocean, caused by its large thermal capacity, is taken into account by such models. Part of the realised temperature increase is delayed by storage of heat in the ocean. In addition the spatial distribution of the greenhouse warming, which is largely influenced by ocean currents, is represented more realistically than is done by other climate models.

Coupled atmospheric-oceanic GCMs have been used for this study in order to give a more realistic description of the expected climatic change. In contrast with the atmospheric GCMs not only the condition of the atmosphere in equilibrium can be given, but also the condition at an arbitrary chosen point in time during the change of the climate caused by the increase of greenhouse gas concentrations. And as long as the greenhouse gas emissions will not have been stabilized, on any arbitrary level whatsoever, the climate system will not be able to reach an equilibrium situation.

So, coupled models give a physically more accurate representation of what in reality is happening. In addition -and this is of particular interest regarding the aim of this study- they allow predictions with an associated timing. Because of these two reasons only results from coupled GCMs have been used for this study.

6.2.1 Descriptions of the models considered

Before processing the quantitative results given by the different models, a short description of these underlying model-simulations -runs in jargon- and some separate results will be given. For technical details, like the used numerical method, difference scheme and parameterisation of the physical processes we refer to the original articles, given in Table 6.2.

Model	Reference
United Kingdom Meteorological Office (UKMO)	Murphy (92)
Geophysical Fluid Dynamics Laboratory (GFDL)	Manabe et al. (91)
Max-Planck-Institut für Meteorologie (MPI)	Cubasch et al. (92)
National Center Atmospheric Research (NCAR)	Washington and Meehl (89)

Table 6.2. The four coupled GCMs of which the results have been used for this study

The model of the Max-Planck Institute für Meteorologie

The MPI model uses a realistically coupled ocean-atmosphere model to calculate climatic changes for emission scenarios A and D. Scenario D assumes stabilisation of the anthropogenic emissions at today's levels, while scenario A, also called the Business-as-Usual scenario, implies a continuation of the actual growth in emissions. Using these scenarios as basis, the time-dependent response of the coupled system to a sudden increase of the atmospheric CO_2 concentration is computed.

The simulations cover a 100-year period. In addition to the three greenhouse-warming experiments a control run simulating the present climate has been carried out as reference. The combined radiative forcing of CO_2 and all other greenhouse gases is expressed in terms of an equivalent atmospheric CO2-concentration.

In general, a warming of the atmosphere is calculated by the MPI model. This warming is largest at the tropical tropopause and at the surface at high latitudes. The warming is significantly larger over land areas than over oceans. It is also characterised by an attenuation in the Southern Hemisphere. The stratosphere shows, as expected from theoretical considerations, an extensive cooling.

More specific results are as follows. The largest temperature increase occurs where the sea ice retreats due to the ice-albedo feedback mechanism. In those regions the albedo, i.e. the reflectivity of the Earth's surface, decreases because of the transformation of sea ice into sea water. Sea water, due to its 'blackness', absorbs solar radiation to a larger extent and, thus, reflects solar radiation to a lesser extent than sea ice. Thence, in this new situation much more sunlight will be absorbed by the Earth, thereby increasing the temperature of the atmosphere. Regions of low warming or even cooling at the surface occur in regions of deep convection at high latitudes, mainly the Northern Atlantic and the Weddell and Ross Sea.

The model of the Geophysical Fluids Dynamics Laboratory

Three 100-year integrations of this model have been performed; two perturbation runs and a control run. The first integration has an increase of the CO_2 concentration with 1% a year; the second one a reduction of the concentration by the same rate. The rate of 1% a year is chosen because the total CO_2-equivalent radiative forcing of the various greenhouse gases other than water vapour is currently increasing at approximately this rate.

Temperature increases in a two times CO_2 climate have been calculated for each Hemisphere. The temperature increase in the Southern Hemisphere appears to lag that of the Northern Hemisphere. The transient response of the sea surface temperature is very slow over the northern North Atlantic and the Circumpolar Ocean of the Southern Hemisphere where vertical mixing of water penetrates deeply and the effective oceanic thermal inertia is large.

The model from the United Kingdom Meteorological Office

The UKMO-model has calculated the time-dependent response of an increase in the CO2-concentration also. The climate change experiment consists of two 75 year-integrations. The first is the control run, in which the CO2-concentration is kept constant. In the anomaly-integration a 1% per year increase of CO_2 concentration is prescribed, resulting in a CO2 doubling in 70 years.

The amplitude of the time-dependent response, i.e. the realised warming, at the time of two times CO2 in the atmosphere is generally smaller than the one realised with instantaneous CO2 doubling. This is due to the fact that the Earth's radiative balance has not yet reached equilibrium with the imposed forcing in the time-dependent simulation. Like in simulations with other models a region of less warming over the Northern Atlantic has been calculated. A remarkable result is that for some places at high Southern latitudes a significant cooling has been calculated. As with the other models, the simulated response is smaller in the tropics.

The model of the National Center for Atmospheric Research

With the model of NCAR three simulations have been done covering a period of 30 years; the first with an instantaneous doubling of atmospheric CO2, another with a linearly increasing concentration of CO2 in the atmosphere -rate of increase: 1% a year- and a control run with CO2 held constant. Because the model run takes only 30 years, the point of CO2 doubling has not been reached during the run.

Whereas in the other model simulations the warming is less in the Northern Atlantic, the NCAR simulations calculate even a cooling in the zonal mean for the winter months North of about 30 °N. This cooling is partly due to differences in sea level pressure in a two times CO2 climate, resulting in different circulation patterns. With this new circulation pattern, colder air is brought southward. The maximum cooling occurs near 65 °N. In the experiment with the instantaneous doubling of CO2, this region of cooling is smaller. It is in the time-dependent case that the changes in forcing are much slower and the climate system has a chance to evolve gradually. The time evolution allows more adjustment by the ocean to the gradual changes in the atmospheric circulation.

Model	Rate of CO2 increase	Length of simulation in years	CO2 doubling time in years
MPI	IPCC-90 scenario A (see Figure 5.15)	100	60
GFDL	1% per year	100	70
UKMO	1% per year	75	70
NCAR	1% of initial value per year	30	100

Table 6.3. Characteristics of the model simulations considered.

Flux correction

Three of the models considered (GFDL, MPI, UKMO) make use of adjustments to the oceanic fluxes, like heat and moist. Thus, the ocean temperature and salinity remain close to present climatology. Without these corrections, significant systematic errors may be introduced which may lead to a drift of the simulated present-day climate. The NCAR model does not make use of such corrections. In its simulations such errors do not appear apparently. Comparing the responses of the NCAR model and the other models indicates that the simulated changes in temperature are not substantially affected by the flux adjustment (IPCC 92).

In general, the response of sea surface temperature may be different from that of surface air temperature in high latitudes where sea ice separates air from underlying water. Because of the coarse horizontal resolution of the models, many features influencing the oceanic circulation are only crudely resolved. Bottom topography, for example, is poorly resolved. In addition, advective processes, especially horizontal, are too weak and features such as the Gulf Stream are therefore inadequately represented. Actually, this applies to all models considered.

The flux correction may have a large influence on simulated temperatures. In this respect there is reason to try to attribute a standard deviation to this correction. However, as no quantitative results on the influence of this correction, on either climate forcing or simulated temperatures, could be found, this issue had to be taken to the 'Department of added ignorance'. Section 6.4 will deal with this department.

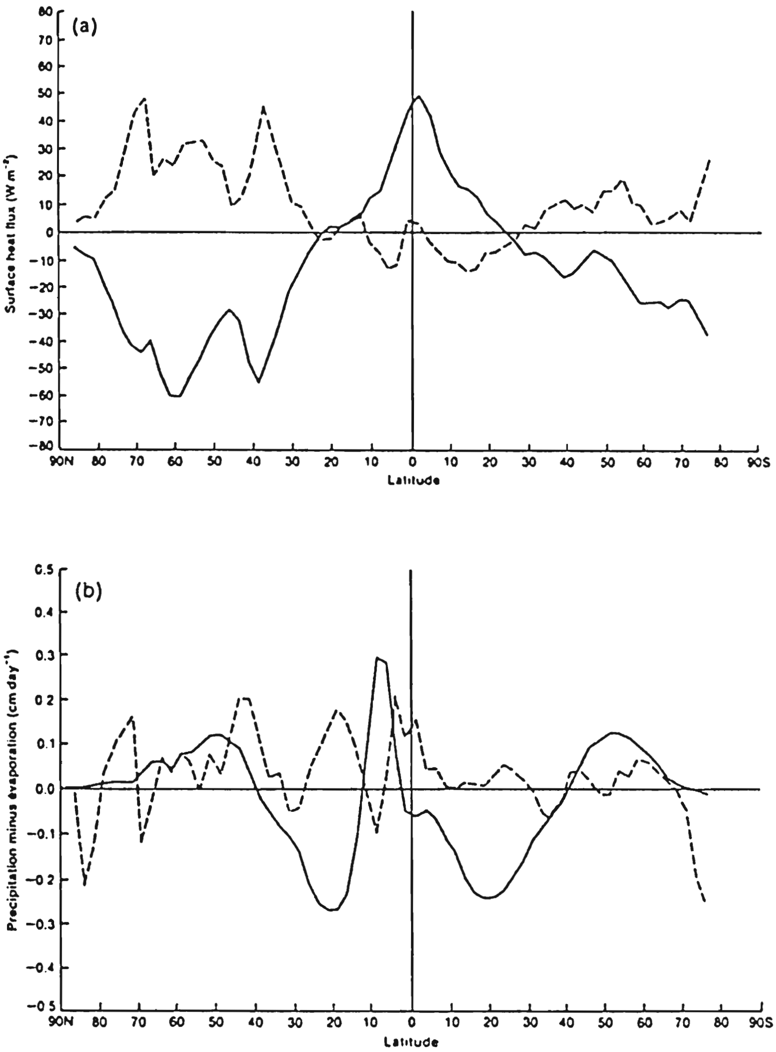


Figure 6.3. Simulated zonally averaged fluxes (solid line) of (a) heat and (b) moist and the flux corrections added (dashed line) during a run with the UKMO model (IPCC 92).

6.2.2 Qualitative results

6.2.2.1 Global response pattern

The coupled models give the smallest temperature response in the tropics, just like the non-coupled models. The spatial patterns obtained with the coupled models are about the same as the patterns of atmospheric models also, but with a smaller response caused by the retarding effect of the oceans (IPCC 92). Reasons for this global response pattern, i.e. the higher the latitude the stronger the warming, are as follows.

- The snow/ice-albedo feedback has a positive effect on temperature increases. When the temperature increases, the amount of snow and ice will decrease. This results in lower albedos, leading again to a larger temperature increase, which may lead.....
- In the tropics, a greater proportion of the surface radiative-heating is used to increase evaporation, rather than to raise surface temperature; the increased evaporative cooling reduces the surface warming relative to higher latitudes.
- At higher latitudes the atmosphere is more stable in the sense that vertical motion -convection- is less strong. In the tropics the warming is transferred more efficiently to the upper troposphere due to enhanced latent heat release, i.e. the release of heat due to phase changes of water, e.g when water vapour condenses into liquid water, in convective processes.

list 6-4

6.2.2.2 Temperature response in the North Atlantic

The most pronounced results of the model integrations exist in the Northern Atlantic and the Circumpolar Ocean of the Southern Hemisphere. In those areas the results of the models show a relatively small warming or even a cooling. This can be understood by two mechanisms, which will be elaborated for the North Atlantic case.

- In the North Atlantic heat generated by a warming of the atmosphere penetrates locally very deeply, caused by strong vertical mixing. The stored heat is spread over a deep water column thereby reducing the warming of the surface waters.
- Relative to the control run, the Northern Hemispheric thermohaline circulation weakens during the perturbation run. This circulation exists of a northward transport of warm saline sub-tropical water in the upper ocean, a sinking branch at 60 °N coincident with deep water formation, and a compensating southward return flow at depth. The weakening of this circulation is caused by an increase in the net surface fresh water flux; especially at high latitudes an excess of precipitation over evaporation is created by the warming of the atmosphere. This leads to reduced salinity, increasing the stability of the water column, thereby inhibiting the deep mixing which drives the thermohaline circulation. This circulation also becomes weaker as a result of the decreased temperature gradient due to a more pronounced warming at higher latitudes. Consequently, the Gulf Stream will be less intense resulting in a diminished supply of tropical warm water. This mechanism is counteracting the global warming locally.

list 6-5

The temperature response as calculated by the GFDL model is presented in Figure 6.4. The warming of the Southern Hemisphere lags the warming of the Northern Hemisphere; this is especially clear at the Poles. This lag is due to the large amount of ocean water at the Southern Hemisphere, having a retarding effect on the warming. In the Northern Atlantic the temperature increase is less than in other parts of the latitudinal band. The winds in this region are most of the times westerlies, i.e. the weather in Western Europe is coming from the Atlantic Ocean. So when the Atlantic is cooler this will influence the weather in Europe. Though it is mainly Scandinavia which will be influenced by this relative cooling, this effect applies equally but to a lesser extent to the remaining parts of Western Europe. In other words, the temperature change in Western Europe will probably be less than the zonal mean change.

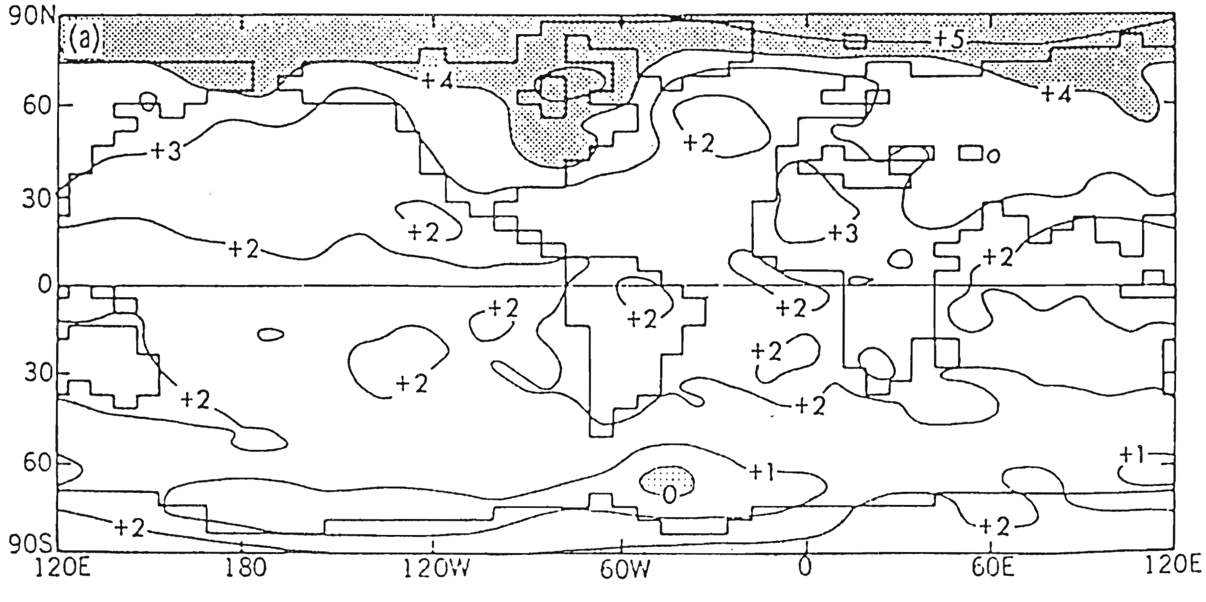


Figure 6.4. The response of the temperature of the coupled GCM of GFDL to a 1% yearly CO2 increase (Manabe et al. 91); situation at the time of CO2 doubling.

6.2.3 Quantitative results

The results of the experiments with the coupled GCMs described above have been used to obtain the global mean temperature increase associated with a CO_2 doubling. Three of the four model integrations have reached the point of CO_2 doubling during the integrations. The NCAR study only gives results of the first 30 years of the run at which point CO2 doubling has not yet been reached. A projected warming at the point of CO2 doubling for the NCAR model is given by the IPCC 92 report. In Table 6.4 the results are summarised. It should be kept in mind that those values represent the temperature increase -the averaging 10 years of simulated temperatures to compensate for the large model variability- at the point of CO_2 doubling, but that the system is not yet in equilibrium then, if ever. Consequently, the temperature will most likely continue to increase. In Murphy (92) the realised fraction of the equilibrium response is given for three coupled models, which gives 57 ±5%. The temperature increase is the increase during the CO2 doubling time, being the difference between the results of the run with increased CO2 and the control run, in which the CO_2 concentration is held constant.

Model	ΔT_{global} (°C)	ΔT_{zonal} (°C)	$\Delta T_{regional}$ (°C)	$\Delta T_{reg}/\Delta T_{glo}$
MPI	+1,3	-	+1,5	1,15
GFDL	+2,3	+3,5	+3	1,30
UKMO	+1,7	-	+2	1,18
NCAR	+2,3	-	-	-
Average	+1,9 ±0,5	-	+2,2 ±0,8	1,2 ±0,1

Table 6.4. Results for the temperature increase at double CO2 on three spatial scales. The ratio between the temperature increase on regional scale and that on global scale is given also. Values are averaged over the models.

Model results on the global scale

The value of the temperature increase on the global scale that will be used for this study is the calculated average of the four values given in Table 6.4. This implies that the same weight is given to the four models. Although the models considered do not have the same characteristics (see Table 6.3 on page 82) this assumption can be justified by the fact that there is no reason to believe that one model simulates the future climate more accurately than the others. This results in:

$$\Delta T_{global} = +1.9 \pm 0.5 \text{ °C}.$$

The equilibrium response of the climate under CO2 doubling according to the models is:

$$\Delta T_{global,\ equilibrium} = +3.3 \pm 0.9 \text{ °C}.$$

The accompanying standard deviation represents the spread of the four values (see equation 6.1 on page 77). Figure 6.5 presents the time evolution of the global mean temperature change according to the MPI model.

Model results on regional scales

Temperature increases on regional scales has also been obtained. Unfortunately, they will be less secure than the global mean values. The studies considered do not give values for smaller scales, e.g. for regions of the size of Western Europe. So the value for this region had to be taken from direct reading of the figures in the respective articles. We acknowledge that this is not the most precise method imaginable.
No value of the NCAR simulation was available: the model run simulated only the first 30 years. So in Table 6.4 only the regional results of the other three models are given. The average of these three values is:

$$\Delta T_{regional} = +2.2 \pm 0.8 \text{ °C}$$

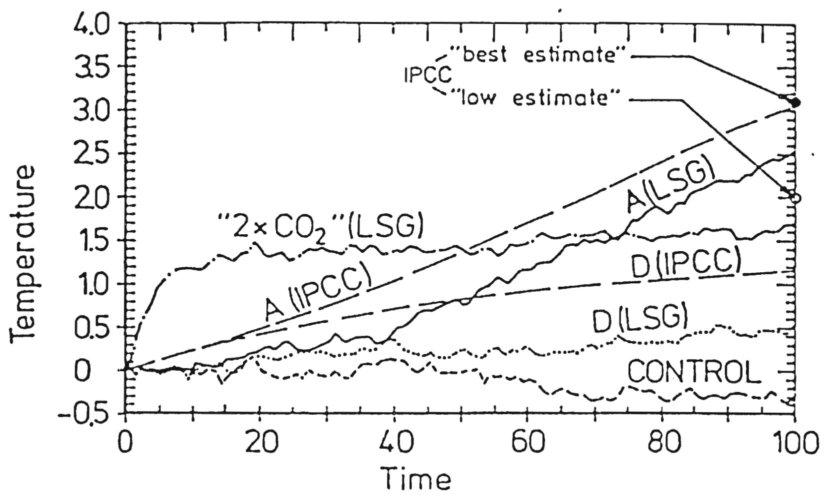


Figure 6.5. Timely evolution in years of the global mean temperature change in degrees Celsius (°C) for three greenhouse warming simulations (A, D, and 2xCO2 (LSG)), the control experiment, and the IPCC 'best estimates' (A and D (IPCC)) (Cubasch et al. 92).

The ratio which relates the temperature increase in Western Europe with the global mean temperature increase has also been calculated. It is given in the last column of Table 6.4. The results of the three models agree well. Calculating the mean gives: +1.2 ±0.1 °C. So according to the models the temperature increase in Western Europe is roughly 1.2 times the global temperature increase. As the models agree well at this point there is no reason to introduce an additional standard deviation. The ratio as calculated from palaeo-climatologic studies is given in Section 6.6.

Model results on zonal scales

Quantitative model results of the latitudinally averaged temperature increase in a two times CO_2 climate are sparse. Only GFDL gives the temporal variation of the change in zonally averaged, decadal-mean temperature, both for surface air and the sea surface. The values for the surface air temperature are presented in Figure 6.6; the surface air temperature at the point of CO2 doubling at 53N has been estimated from this figure:

$\Delta T = +3.5 \pm 0.5$ °C

The associated standard deviation is due to the reading error. According to the GFDL-model, the greenhouse warming is less in the region of interest for this study, than for the latitudinal band to which this region belongs as a whole. When the temperature distributions of the other models are examined the same seems to be true.
The ratio $\Delta T_{zonal}/\Delta T_{global}$ for the GFDL model is 1.5. In Section 6.6 this ratio as it follows from palaeo-climatologic considerations will be given. Because this value is obtained from only one model result, the standard deviation should be higher than the reading error as given earlier in this section. Examining whether the GFDL made a reliable prognoses for the regional temperature increase by comparison with results from other models leads to the conclusion that this is indeed the case: the factor $\Delta T_{regional}/\Delta T_{global}$ according to GFDL is 1.3 while the average of all models gives 1.2. This high degree of between-model agreement gives some allowance to base the result for the zonal scale on one model simulation only.
The standard deviation will be somewhat higher than it should probably have been with more results available. In addition, it follows from theory that the standard deviation as calculated for the regional scale should be higher than for the zonal scale. As only one value is available for the zonal scale, the value for the standard deviation is assumed to be similar to that for the regional scale, i.e. 0.8 °C. Combining the ratio $\Delta T_{zonal}/\Delta T_{global}$ of 1.5 with the global mean temperature increase of 1.9 °C and incorporating the estimate for the standard deviation, this leads to $\Delta T_{zonal} = +2.8 \pm 0.8$ °C.

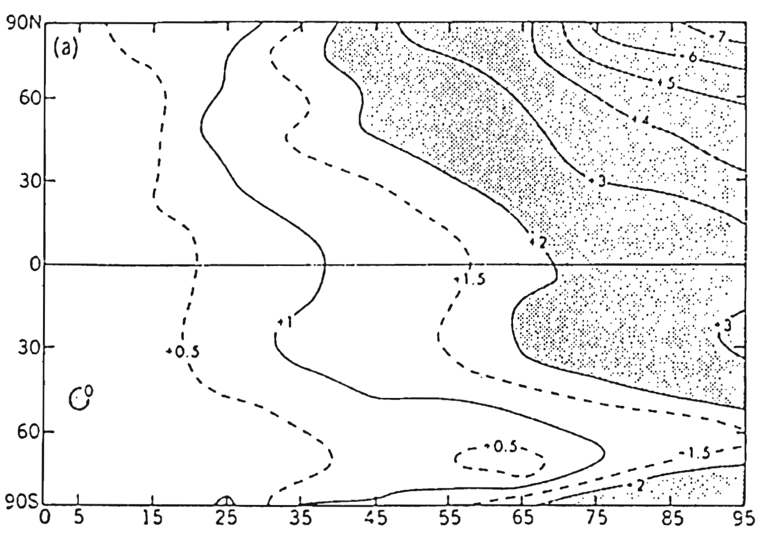


Figure 6.6. The temporal variation of the differences in zonally averaged, decadal mean surface air temperature in degrees Celsius (°C). The years of the model simulation, i.e. the modelled years, are indicated on the horizontal axis (Manabe et al. 91).

Summary of the model results

The results are summarized in Table 6.5. The temperature increase in a two times CO2 climate in Western Europe is somewhat less than averaged over the latitudinal band. This is caused by the relative cooling over the North Atlantic, which influences the weather in Western Europe. The global mean temperature increase is smaller than the increases calculated for the other two cases. This is caused by the the fact that the temperature increase on the Southern Hemisphere is less than that on the Northern Hemisphere. Another reason is the relatively strong temperature increase at higher latitudes in the Northern Hemisphere which have been analysed for this study.

Geographical scale	ΔT in °C	σ in °C
Global	+1.9	±0.5
Zonal	+2.8	±0.8
Regional	+2.2	±0.8

Table 6.5. The temperature increase on three spatial scales based on model results, with the accompanying standard deviation σ.

6.3 Added wisdom

The following processes or forcing mechanisms, which not yet have been accounted for in the (individual runs with) coupled models, have been identified as having a fairly large impact on model output if they will eventually be included in the models:

1) natural variability,
2) anthropogenic aerosols,
3) sensitivity on the initial conditions,
4) the cold-start phenomenon,
5) emission rates of greenhouse gases, and
6) the physical and statistical representation of clouds.

A quantitative assessment of the influence of these processes on the model predictions lead to a reduction of the most probable temperature in 2050 by 0.1 °C and a concomitant increase in the 95% confidence interval of 1.6 °C (both temperature values account for the global situation and for the situation in Western Europe).

list 6-6

The purpose of this section is to add information to the results obtained from the coupled GCMs. This is needed because the parameterisation of certain physical processes which cannot be resolved analytically introduces errors. In other cases, the representation of physical processes playing a role in the climatic system is simply absent. Some of these uncertain factors are quantified by attribution of a standard deviation, representing the possible influence that the uncertain factor can have on the temperature change. Some of them introduce a structural deviation of the predicted change in mean temperature. If so, the calculated temperature changes for CO2 doubling have been adapted. Finally, the additional standard deviations identified for the processes which have been ignored by the models will be combined to produce a final, deterministically obtained standard deviation.

6.3.1 Natural variability

In the climate system the slow components are altered by the fast components, which again are influenced by the slow components, so that the complete system shows a considerable variance just by an interaction of all components involved. This effect is an illustration of 'natural variability'. The concept of natural variability will here be given some more attention for changes in temperature.
Fluctuations of temperature involve mechanisms with characteristic time scales of 100 to 100 million years (Crowly 91). On time scales of 10 million to 100 million years, palaeographic factors (e.g., continental drift and ocean circulation changes) and atmospheric CO_2 changes appear to have played an important role in controlling global fluctuations. On a time scale of 1.000 to 100.000 years the Earth's climate appears to be sensitive to both external forcing by orbital perturbations (the so-called Milankovitch cycles) and internal feedback interactions (including CO_2) within the land-sea-air-ice system.
The future climatic change due to CO2 doubling will not be influenced significantly by the variability on either very large time-scales or smaller time-scales as there is no reason to believe that the temperature effects of the natural climatic variability on these time-scales is significant compared to the temperature effect associated with CO2 doubling. As this doubling is expected to occur in about seventy years, only natural fluctuations on decadal or longer time scales, if significant, will be treated in this section.

6.3.1.1 Volcanism

Volcanoes may explain decadal scale cooling. Detailed studies of large volcanic events over the last hundred years indicate that a global averaged cooling of some tenths of degrees may occur after a large eruption for a period of months to a year typically. The aerosols brought into the atmosphere by the eruption of Mount Pinatubo in June 1991 is agreed on to have ended the years of relatively high global temperatures which started in the late eighties. In addition to these volcanic aerosols, aerosols are brought also into the atmosphere at lower altitudes, the troposphere, by anthropogenic activity. These anthropogenic aerosols will be treated in Paragraph 6.3.2 together with the general effects of aerosols. The main difference between the two types of aerosols is the time they remain in the atmosphere. For the anthropogenic aerosols this time is very short. Volcanoes may belche the aerosols into the high stratosphere. From these altitudes, removal processes are much slower than in the troposphere.

Volcanic events, even very large ones, often do not have a global scale effect. But then, it may be argued that some of the inter-hemispheric differences in climate records could reflect the more localised forcing in one hemisphere. Detectable direct temperature effects are manifested in only the first years after an eruption. However, through some type of ice-albedo feedback, in which short-term cooling events affect sea-ice cover, the effect may theoretically be felt over decades, because of the longer time constant of sea-ice. Main difficulty with predicting the climatic effect due to volcanism is the absence of periodicity. It can not be predicted when or where there will be a volcanic eruption and how many aerosols this eruption will bring into the stratosphere. In Figure 6.8b, a connection is given between time and 'Lamb's volcanic dust-veil index', which is a measure for the volcanic dust concentration.

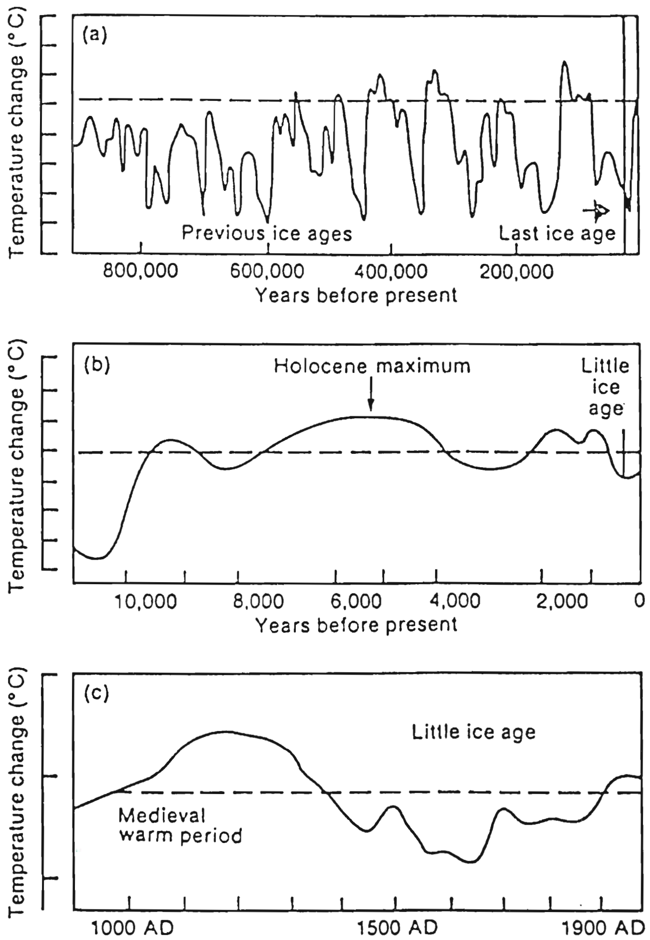


Figure 6.7. Global temperature variations during the last million years (**a**), the last ten thousand years (**b**), and the last thousand years (**c**). The dotted line represents conditions near the beginning of the twentieth century (IPCC 90).

6.3.1.2 Solar variability

Solar variability is suggested as an alternative explanation for climatic variability. A 1% change in total irradiance should be equivalent to a radiative forcing of 2.4 watt per square metre at the top of the troposphere, comparable to the total enhanced greenhouse forcing to date.

A correlation has been found between the variable period of a 11-year sunspot cycle and the mean Northern Hemisphere land surface temperature from 1865 to 1985 .There is also a suggestion that low-frequency irradiance changes run parallel to the envelope of sunspot activity, which shows quasi-cyclic behaviour with a roughly 80-years period. Sunspots are paired off with solar flares. So the more sunspots we have, the more solar flares we have, netto giving a higher solar activity. But at a certain quantity of sunspots, this relation is not true anymore. The envelope of sunspots is known as the Gleissberg cycle. Both the 11-years- and the 80-years cycle are shown in Figure 6.8a.

The remarkable feature in Figure 6a is the relative absence of sunspots from about 1645 to 1715, the so-called Maunder minimum. This event runs parallel to the coldest period of the Little Ice Age, a colder period which lasted from about 1500 to 1900. The warming which the climate currently undergoes is sometimes seen as a recovery of this colder period. The precisely-dated record of atmospheric radiocarbon measurements shows that similar periods of prolonged sunspot minima have occurred on many occasions during the past 8000 years (randomly spaced, but every 500 years on average). Nonetheless all these suggested mechanisms of solar variability, it is questionable whether the resulting forcing factors are large enough to create natural variability which is significant in the context of the forcing due to the predicted CO2 doubling. Indeed, climatic influences proposed, for example the Gleissberg cycle, lack a physical explanation that could lead to the claimed relation.

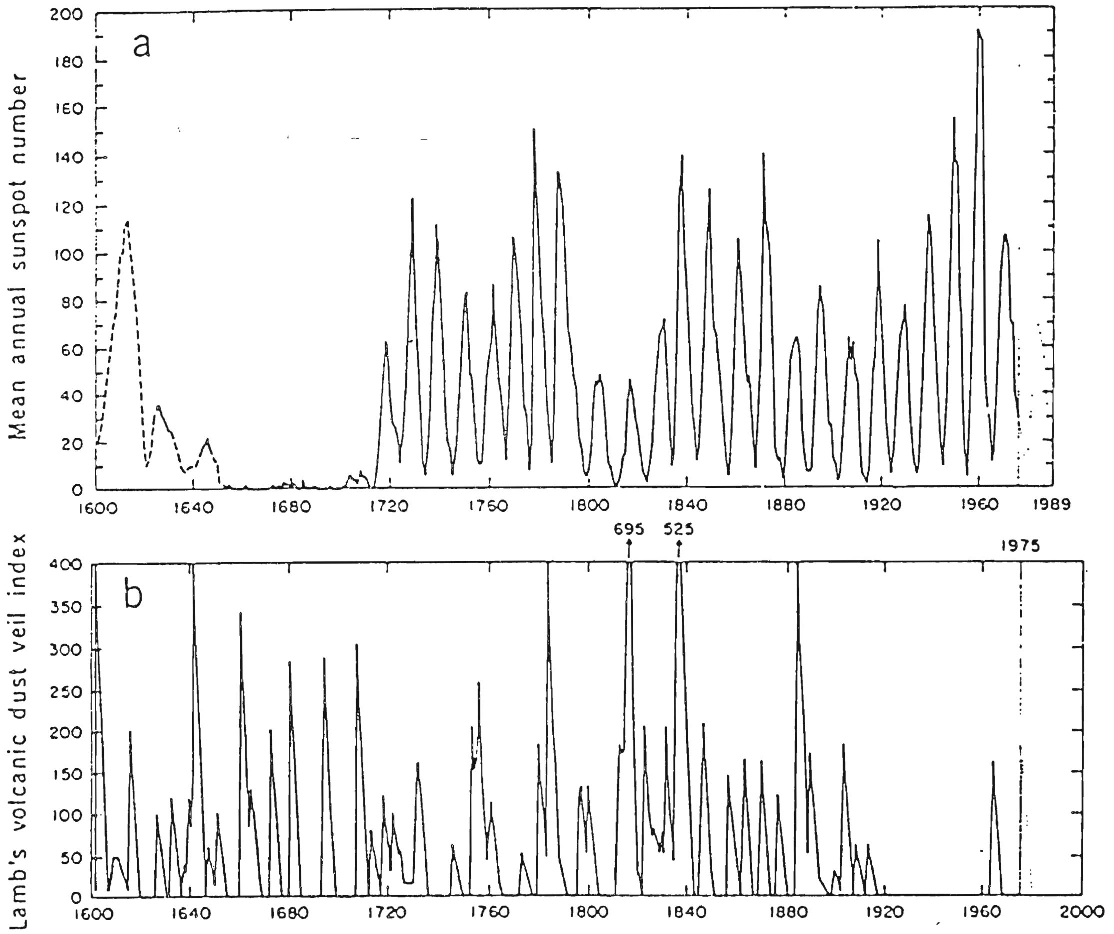


Figure 6.8. Mean annual sunspot number (**a**) and the Lamb's volcanic dust veil index (**b**).

6.3.1.3 The El Niño-Southern Oscillation phenomenon

On a time scale of only a few years climatic variability is largely determined by a phenomenon called El Niño-Southern Oscillation or ENSO. This irregular oscillation has significant consequences even on the global scale. In the Southern Hemisphere, about 20 to 30% of the yearly temperature fluctuations is linked to the Southern Oscillation. ENSO is an internal variation that may be regarded as a free oscillation of the ocean-atmosphere system. ENSO is one global scale oscillation consisting of two components. The first, known as El Niño, has as result that the normally cold waters over the entire eastern equatorial Pacific Ocean show a warming of several degrees. Associated with these changes are anomalies in the atmospheric and ocean circulation. The second component of ENSO, the Southern Oscillation, is mainly atmospheric. It is associated with large East-West shifts of mass in the tropical atmosphere between the Indian and West Pacific oceans and the East Pacific ocean. An opposite phase of 'cold events', with opposite patterns of the Southern Oscillation, is generally referred to as La Niña. ENSO events occur every three to ten years and have far reaching climatic and economic influences around the world. The mechanism of ENSO is still not fully elucidated. For example it is not known whether ENSO starts in the ocean or in the atmosphere. There are periods with and without the oscillation. The current situation is that when the Southern Oscillation is accounted for in the models, there is a continuous oscillation. This does not agree with reality.

6.3.1.4 Quantitative results

Whether the temperature increase of the last century of about 0.5 °C (IPCC 90), as shown in Figure 6.9, is due to the CO_2 effect is not certain. It is also possible that it is caused by natural variability. However, such rapid temperature change has not occurred in the known past. Because of the short length of individual climate series with a good accuracy, it is impossible to get sufficient understanding of natural variability on larger time-scales. Any climate prediction which will be made for the future climate will be uncertain because of imperfect knowledge of natural variability. The sources of natural variability as identified in the previous section will be quantified in the following way. When the uncertainty arising from natural variability in the climate prediction has to be determined, a possibility is to assume that all variation having occurred in the past is caused by natural effects. This includes the variation on century long time-scales, i.e. the observed temperature increase of 0.5 °C over the last century. Then we may be confident that the calculated uncertainty is not too small, that is, unless the natural variability is suppressed by the greenhouse effect, but that has not been assumed for the present study. The standard deviation needed can be calculated in two ways. It is possible to determine a deviation as a result of the yearly fluctuation of the temperature. This standard deviation is useful when you want to give the prediction for a well-defined year.

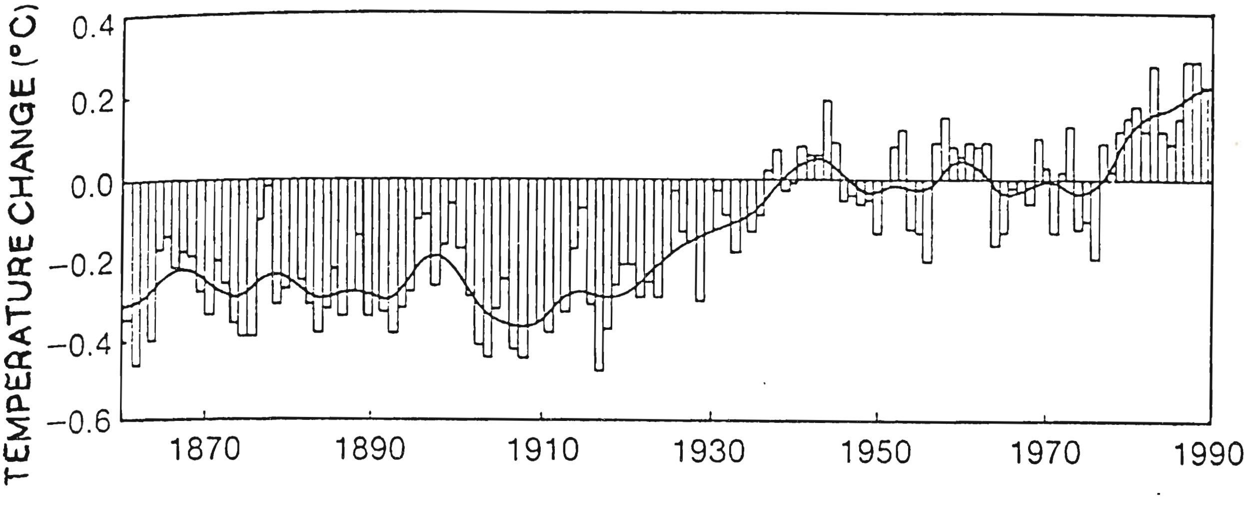


Figure 6.9. Global-mean temperatures for the period 1861 to 1989, relative to the average for the period 1951 to 1980 (IPCC 90).

If the prediction has to be made for a less well defined period in the future, it is probably more useful to calculate the fluctuation of ten-year mean temperatures around the average temperature for a century. Calculations on even larger time-scales can be made also, but these are not of interest for this study because CO_2 doubling is expected to occur in about 70 years.

The calculation of the mean temperature and the accompanying standard deviation has been made for three spatial scales; for the global, the zonal and the regional scale. For this the Climate Disk has been used, which contains values of climatic variables of all meteorological stations in the world, including temperature. Some records even go back to the seventeenth century. With this data, it is possible to calculate the mean temperature of a certain period for a certain region including its standard deviation.

The global temperature history of the elder periods is less accurate due to the uneven station distribution in the Southern Hemisphere, partly due to the fact that oceans have always been poorly represented, and the smaller number of stations for earlier periods. So for reasons of accuracy and global coverage only the data whic have been obtained during the last century have been used for the calculations. The Climate Disk contains both station temperatures and gridded temperatures. The gridded temperatures, i.e. temperatures for grid boxes of 5 degrees in latitude and 5 degrees in longitude, have been used in this study. Thus, The Netherlands can be associated with the grid box representing the geographical area 50N x 55N, 5E x 10E. For this grid box the following calculations have been made:

- The mean temperature for the period 1951 to 1980, including its standard deviation (σ) which originates from the yearly fluctuation around this mean temperature.
- The mean temperature for the period 1900 to 1980, together with the 10-year mean fluctuation around this averaged temperature.

list 6-7

The same has been done for the 53th latitude North, i.e. the area 50N x 55N, -180W x 180E, and for the globe as a whole. The results are listed in Table 5. From the table follows that the smaller the spatial scale, the greater the observed fluctuation. This is in line with what might be expected from theoretical considerations; on larger scales, negatively and positively biased extreme events will average. A hot summer in The Netherlands, for example, may compensate a cold winter in Poland. The standard deviation due to the ten-year mean temperature fluctuation around the longer term mean has been used for this study. Because the timing of CO_2 doubling in the atmosphere cannot be given exactly, the standard deviation of the yearly temperature fluctuation will not be used.

A few remarks should be made on the above results. Firstly, it is assumed that the natural variability in a future greenhouse climate will be the same as it has been in the past century. There are indications for this not being true. According to simulations with the NCAR model, variability calculations with double CO_2 show mostly increases of tropical inter-annual variability and decreases of inter-monthly variability near 60 °N (Meehl et al. 94). These changes in the tropics are partly related to changes in ENSO. However, the results give no indication of an increase or decrease in the global mean natural variability. Also nothing is stated about the natural variability which is of interest for this study, that on the longer temporal scales. On the other side, external forcing factors of the climate like fluctuations in the solar cycle, remain the same in climate under CO_2 doubling.

Area of interest	1951 - 1981 mean temperature (°C)	σ yearly fluctuation (°C)	1900 - 1980 mean temperature (°C)	σ 10-years mean fluctuation (°C)
the Netherlands	9.35	0.50	9.31	0.19
53th latitude	4.64	0.29	4.53	0.18
globe	17.99	0.11	17.88	0.13

Table 6.6. Calculated values of the mean temperatures and the accompanying standard deviation (σ). The standard deviations of both the yearly fluctuation and the 10-years mean fluctuation are presented.

6.3.2 Anthropogenic aerosols

A second source of uncertainty is due to the presence of little particles in the atmosphere; the so-called aerosols. Contrary to the trace gases, which exert a positive radiative forcing, aerosols cause a negative influence on the radiative balance. The total suspended particulate matter in air varies from less than 1 μg per cubic metre over polar ice caps or in the free mid ocean to 1 milligram per metre in desert dust outbreaks or in dense plumes from, for example, forest fires (IPCC 90). Aerosols exist of matter of both anthropogenic and biogenic origin. Here, only the tropospheric anthropogenic aerosols will be dealt with.

6.3.2.1 Properties of aerosols

Stratospheric aerosols and those in the troposphere have different properties. The stratospheric aerosol layer is mainly of biogenic origin; it is maintained by an upward flux of gases following volcanic eruptions. Stratospheric flights of civil aircraft may currently enhance the stratospheric concentration of aerosols significantly in areas where the traffic density is large, e.g. in the North Atlantic Flight Corridor (Hofmann 91). However, relatively few measurements exist to verify this hypothesis. The part of the standard deviation in the predicted temperature the biogenic stratospheric aerosols cause is accounted for by the standard deviation which is due to the natural variability.
Atmospheric aerosols are mainly sulphate aerosols formed by gas-to-particle conversion of sulphur dioxide (SO2) through photochemical processes. Such conversion may take place through oxidation of SO2 and other sulphur gases to sulphuric acid (H_2SO_4) by reaction with hydroxide (OH). SO2 emissions amount to some 70 - 80 Teragrams of sulphur per year, mainly from fossil fuel combustion.
Aerosols constitute their own class of substances with different size-distributions, shape, chemical compositions and optical properties. Concentrations vary by orders of magnitude in both space and time. Observations of their temporal and spatial variation are poor. Thus, the uncertainty in the calculation of the radiative forcing due to changes in aerosol concentrations may expected to be large in advance. The negative forcing aerosols exert is due to:

1) Direct radiative influence:
    Aerosols increase the reflection of short-wave or solar radiation to space, resulting in a globally averaged forcing from -0.9 to -0.3 watt per square metre (Table 6.7).
2) Indirect radiative influence:
    When clouds form in air with increased aerosol concentrations, their reflectivity is enhanced because of the increased concentrations of cloud condensation nuclei (CCN). These CCN are little particles on which water vapor may condence. This enhanced reflectivity is caused by the larger concentration of smaller droplets. The droplets become smaller because the liquid water content remains the same, while the amount of condensation nuclei increases. The magnitude of this indirect effect is difficult to estimate. It may be as strong as the direct effect (Kiehl and Briegleb 93, Jones et al. 94).
    Because the droplet distributions are shifted towards smaller sizes, polluted clouds are less likely to produce drizzle and thus are less likely to rain out. This may lead to longer average cloud lifetime and, thus, to an increase in average cloud cover and so to an increase in the reflection from cloudy regions (Stephens 94). Calculating the contribution of this subtle effect is difficult.
    When more aerosols are present in the atmosphere, the amount of CCN is increased. This may lead to an increase in the average cloud coverage.

list 6-8

Aerosol particles absorb long-wave radiation also, which may lead to a warming effect. This effect is usually small because:

- Aerosols are mostly concentrated in the lower troposphere where the atmospheric temperature, which governs emission, is practically the same as the surface temperature. The energy of the absorbed radiation is then about the same as the energy of the emitted radiation, leading to a net negligible effect.
- The opacity of aerosols decreases at longer wavelengths. The aerosols seems to be less concerned about the long wave radiation than about the short wave.

list 6-9

So, although scientists agree that aerosol increases cause a negative radiative forcing, the magnitude of this forcing is far more difficult to assess than that of the trace gases. Unlike most greenhouse gases, tropospheric aerosols are relatively short-lived; due to effective removal mechanisms their residence time is in the order of a few days only. This leads to two effects:

- High aerosol concentrations can be detected around emission sources. As 90% of SO2 is emitted above the Northern Hemisphere, highest aerosol concentrations can be found there.
- In the future the effect of aerosols will decrease relative to the effect of greenhouse gases. This can be explained as resulting in a faster temperature increase. Alternatively, in the past the greenhouse effect may have been underestimated, because the aerosols were not included in the calculations. This results in an underestimate of the climate sensitivity with respect to the greeenhouse gases. When the greenhouse effect increases relative to the aerosol effect, the temperature will increase faster than expected.

list 6-10

Future changes in the forcing due to changes in atmospheric concentrations of both aerosols and greenhouse gases will depend on how the corresponding emissions vary. Atmospheric concentrations of aerosols will adjust within weeks to changes in emissions.

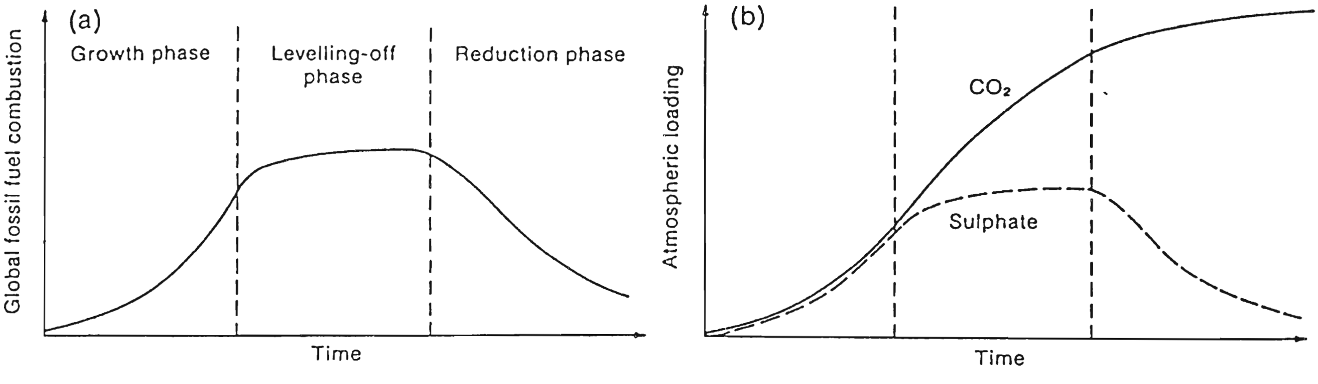


Figure 6.10. Response times of climate forcing due to sulphate (cooling) and CO2 (heating) during different phases of fossil fuel consumption (IPCC 92).

This is a very different situation from that for many greenhouse gases which have lifetimes in the order of decades to centuries. As result, the atmospheric concentration of, for example, CO_2 will continue to rise for more than a century even if emissions are kept constant at today's level. This is illustrated in Figure 6.10.

6.3.2.2 Quantitative results

An estimate of the radiative forcing due to the effects described in the previous section will be given. If the radiative forcing, which is imposed in the climate models and which is due to changes in CO_2, is already corrected for the aerosol forcing, the only effect will be that the point in time at which the magnitude of the radiative forcing, associated with CO_2 doubling will be reached, is postponed for some years. This is not a satisfactory approach, however, as it does not fit in with the fact that the radiative forcing of the greenhouse gases is much more globally determined than that of the aerosols which, due to their short atmospheric residence times, has a much more local character.
and that of the aerosols are distinguished.
The aerosol concentrations show a spatially very dynamical pattern. So it seems logical to split up the aerosol effects on global, zonal and regional scales. In the Northern Hemisphere, for example, and especially above the industrial regions, the effects will be strong, whereas above some other parts of the world they may be totally absent. In Figure 6.11 the industrial regions above Europe, the East of the United States and Japan can be clearly seen, because of the relatively high emissions of gases leading to enhanced concentrations of tropospheric aerosols. Some quantitative radiative results of studies on aerosol effects will be given in the following paragraphs.

Quantitative results on a global scale

Some studies in which values for the globally averaged radiative forcing caused by the direct effect of changes in aerosol concentrations between the pre-industrial situation and the present have been found. The results are presented in Table 6.7.

Study	$\Delta F_{\text{global mean}}$ in watt per square metre
Charlson et al. 91	-0.6
Kiehl and Briegleb 93	-0.3
Taylor and Penner 94	-0.9
Hansen et al. in IPCC 94	-0.25

Table 6.7. Values for the change in globally averaged mean radiative forcing due to changes in aerosols between the pre-industrial period and the present.

With the values for the radiative forcing presented in Table 6.7 an average, including the standard deviation, can be calculated. The standard deviation arises from differences between the calculated values (equation 6.2 on page 77). This gives:

$$\Delta F_{\text{global mean}} = -0.5 \pm 0.3 \text{ watt per square metre}$$

In this same period, the radiative forcing of greenhouse gases is 2.4 ± 0.4 watt per square metre (IPCC 90). So it can be stated that the effect of the greenhouse gases is compensated for 20% by the anthropogenic aerosols. Note that it may still be possible that all results point at the same direction, e.g. a global cooling of less than a watt per square metre, which may nonetheless be the wrong direction.

In the context of this report, which is basically to calculate the temperature change for a two times CO_2 climate, the question is till what extent the aerosols will compensate increases in greenhouse gases under CO_2 doubling. For this, it is assumed that in the future the greenhouse effect will for 10% be compensated by these man-made aerosols. This assumption is based on the following. The radiative forcing will increase due to an increase of greenhouse gas concentrations with a magnitude equivalent to a CO_2 doubling. The radiative forcing caused by the sulphate aerosols under CO_2 doubling is estimated to be the same as it is at present.

The scenarios for the sulphur emissions predict a levelling (IPCC 94), or maybe a little decrease because of the attention given to the acidification of precipitation which stresses the need for reductions in emissions of gases containing both sulphur and nitrogen, which are precursor gases of the aerosols. So, the compensation of the greenhouse effect by man-made aerosols is decreased by 10%. In quantitative terms, this is as follows. The radiative forcing, caused by a doubling of the CO_2 concentration is 4.3 watt per square metre (IPCC 90). The radiative forcing due to the increase in aerosol concentrations which has occurred in the recent past is -0.5 ± 0.3 watt per square metre. As mentioned above it is assumed that this value will not change in the foreseeable future. The relative radiative effect of the aerosols can thus be calculated.

0.5 watt per square metre divided by 4.3 watt times 100% is an 11.6% decrease of the greenhouse gas forcing increase due to increases in aerosols. This agrees well with the assumption of 10%. 0.3 watt divided by 4.3 watt times 100% makes 6.6% as its standard deviation. Runs with coupled GCMs result in a global mean temperature increase of 1.9 °C under CO2 doubling. Hence, the associated direct aerosol effect on this global mean temperature increase is -0.22 ± 0.13 °C.

The indirect effects of anthropogenic aerosols are even less certain. Available estimates show that the indirect effect of aerosols might be of similar size to the direct effect (IPCC 94). Thence it is assumed that the effect on the temperature increase is -0.2 °C also. Because of the larger uncertainty, the standard deviation in this value is assumed to have the same value as the temperature correction, i.e. 0.2 °C.

Now the combined direct and indirect effect of the aerosols can be calculated. Two times a temperature decrease of -0.2 °C leads to a final temperature decrease of -0.4 °C. The accompanying standard deviation has also been calculated. The direct effect gives 0.13 and the indirect effect gives 0.2 °C. Because those two are interdependent, the combined standard deviation is the sum. Consequently, the final temperature effect of the aerosol effect on the global scale is -0.4 ± 0.3 °C.

This approach is not without flaws. For instance, it is assumed that the forcing caused by aerosols leads to the same (relative) temperature effect as the forcing caused by greenhouse gases. Arguments for this relation not being true can be found in recent literature (Taylor and Penner 94). Another point is that the assumptions with respect to changes in forcing due to current and future aerosol increases are very sensitive to the assumed vertical distribution of the aerosols. An aerosol layer at an altitude of 10 kilometres will have a larger effect on the radiative balance than the same layer at an altitude of 1 kilometre, because of the larger temperature difference in the former case. It is this temperature difference which largely governs the radiative effect.

Quantitative results on smaller scales

Depending on the atmospheric concentrations, the radiative effect of the anthropogenic aerosols varies from one region to another. In the Southern Hemisphere, for instance, the effects are small, but in industrial regions the aerosol effect may dominate the greenhouse effect (see Figure 6.11).

From the articles of Taylor and Penner (94), Charlson (91) and Kiehl and Briegleb (93), an increase in forcing of -4 ± 2.6 watt per square metre for the pre-industrial period to the present has been calculated for the situation in Europe. A response to this value by the climatic system may theoretically have resulted in a decrease of the temperature in Europe during the same period, because this effect is stronger than the enhancement of greenhouse effect, which had an estimated forcing of 2.4 watt per square metre in this period. However, when the temperature record for an arbitrary place in the North-Western part of Europe is analysed a temperature increase can be observed for the past 100 years. This indicates that the temperature is not only determined by the magnitude of the solar irradiance, but also by dynamical effects like the advection of air from other places. These become more important on smaller scales.

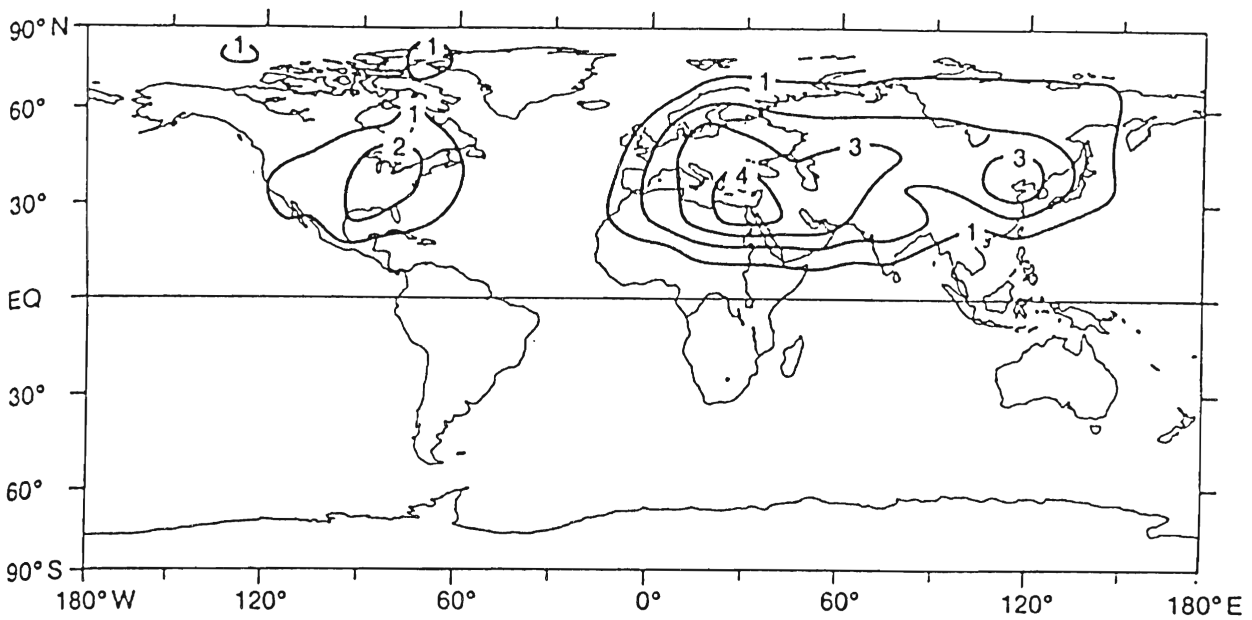


Figure 6.11. Increase in radiative forcing due to increases in anthropogenic aerosols, expressed in watts per square metre (Charlson et al. 91).

The smaller the local scale that is analysed, the more complex the relation between the forcing and the change in temperature is. On larger scales, these dynamical effects may compensate. Because of the large uncertainty with respect to the aerosol effects it is very difficult to give accurate results. The following solution is given to this problem. The temperature correction on smaller scales is assumed to be the same as that on the global scale. The accompanying standard deviation on the regional scale is assumed to be twice the one that is associated with the global scale. It may be expected that the standard deviation on zonal scales is smaller than that on regional scales, because some of the described dynamical effects may be compensated. At the same time, it should be larger than that on the global scale. In this context, the value of -0.4 ˚C seems to be reasonable.

Summary of the radiative effects of anthropogenic aerosols

Aerosol effects for different scales have been calculated. They have been expressed quantitatively by a correction of the temperature increase and by a change in the associated standard deviation. These values are summarized in Table 6.8. Note that on the regional scale, a negative temperature effect is also possible within the 1-σ range. This should be considered as an artefact of the method used in particular, and not so much as a possibility based on research results, though some studies indicate significant indirect warming effects of aerosols due to influences on optical properties of cirrus clouds (Jensen and Toon, 92).

Effect	ΔT correction (˚C)	component of σ(˚C)
Direct effect (globally)	-0.2	±0.1
Indirect effect (globally)	-0.2	±0.2
Total aerosol effect:		
Global	-0.4	±0.3
Zonal	-0.4	±0.4
Regional	-0.4	±0.6

Table 6.8. The effects of aerosols on the temperature at the point of CO2 doubling.

6.3.3 Sensitivity on initial conditions

It is known from the work of, among other persons, Lorenz that the results of models consisting of three differential equations only are highly sensitive to the initial conditions. Because of the non linearity of the system, the results of different runs can vary substantially as a result of uncertainty in the initial conditions.

This type of uncertainty is often analysed with the Monte Carlo technique; a technique used a lot in weather forecasting. The technique comes down to performing an ensemble of model runs. The only difference between these simulations is a slight variation in initial conditions. This variation should be made because the exact conditions of the present atmospheric conditions are not well known. The variation in the model output is called the "between experiment variability". The most often occurring atmospheric circulation pattern, which follows from analysis of the model output, is assumed to be the most probable. With reference to this pattern, the weather forecast will be made. In this section, a study based on this technique will be used in order to obtain the sensitivity to the initial conditions in simulations of the future climate.

Methodology

The source of uncertainty described in this section results solely from imperfect knowledge of the initial conditions of the atmosphere-ocean system. The question which will be addressed is till what extent these different initial conditions prescribe the climatic change over the next hundred years or so. The study of this kind of uncertainty using climate models is new; the results could be based on one study only (Cubasch et al. 94). Cubasch et al. uses a 100-year control simulation in order to obtain initial conditions for the Monte Carlo experiments. Four greenhouse warming experiments have been performed with identical radiative forcing scenarios, i.e. IPCC-90 scenario A. The initial conditions of the four runs correspond to years 0, 30, 60 and 90 of the control experiment. All four experiments were run for 50 years (see Figure 6.12).

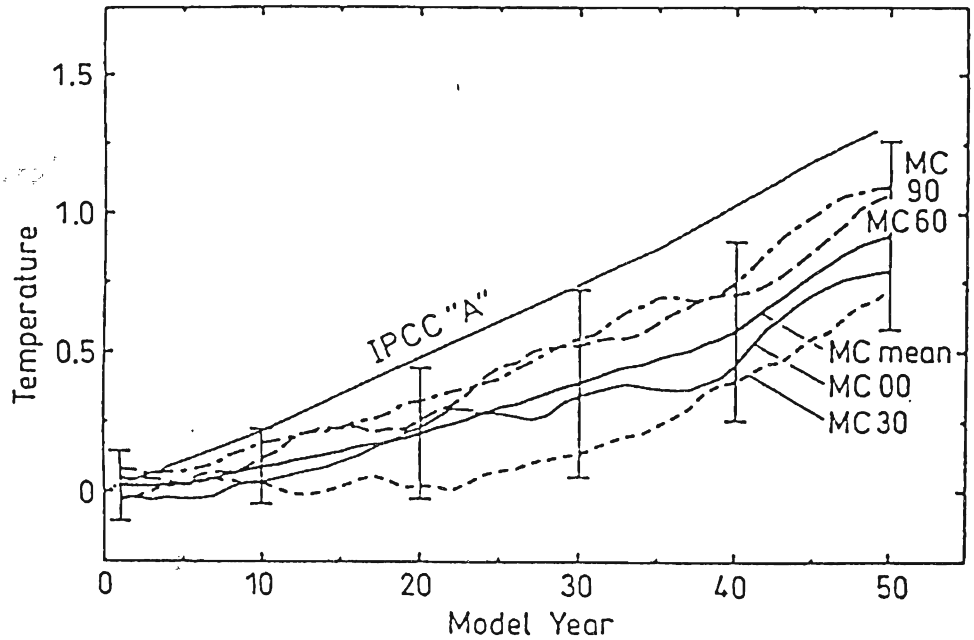


Figure 6.12. Timely evolution of the global mean surface temperature change in degrees Celsius for an ensemble of four Monte-Carlo simulations (MC 00, 30, 60 and 90), the mean over all four simulations (MC mean) including its 95% confidence interval, and the IPCC 'best estimate' (IPCC "A") (Cubasch et al. 94).

Quantitative results on the global scale

The standard deviation originating from differences in initial conditions is obtained from Figure 6.12. The 95% confidence interval, i.e. four times the standard deviation, is also presented. Based on the results by Cubasch et al. after 50 years of simulation, a standard deviation of 0.2 °C is attributed to the "between-experiment" variability. It is assumed that the standard deviation will maintain this value till the time of CO2 doubling, i.e. until 70 simulated years. To be more certain that the standard deviation is still the same after this period, the model should be run for a longer time.

Yet another assumption is that the standard deviation obtained with help of the MPI model is the same as the arising standard deviation in the average of all four coupled models. Because this kind of experiments has not been done more often, this assumption seems to be justified. However, to obtain more certainty about the standard deviation, results from more experiments are needed.

The standard deviation associated with the senstivity of the models on initial conditions is obtained in this section with help of an ensemble of four simulations with the MPI model. However, for calculating the changes in mean temperature due to a doubling of CO2, an ensemble of four simulations had already been used, although from four models. So possibly a correction had already been made for the sensitivity on the initial conditions by processing the results of four individual runs. In that case, the increase of the standard deviation as it is calculated here should be adapted to a somewhat lower value. Since we do not know whether all individual temperature effects obtained where randomly distributed over all possible temperature realisations both calculated standard deviations have been used for the full extent to be certain enough that the final range as bounded by the values defining one standard deviation or one sigma (1-σ) encompasses the realisations to the largest possible extent.

Quantitative results on smaller scales

Cubasch describes the differences in the regional distribution of the temperature change for the last 10 years between the four runs of the Monte-Carlo experiments. The smallest standard deviation between these experiments tends to occur in the tropics. The maximum between-integration standard deviation is at high latitudes in the Northern and Southern Hemisphere. Cubasch ascribes differences in the Arctic temperature signal at least partially to changes in sea-ice volume. Figure 6.13 contains the regional distribution of the "between-experiment" standard deviation of the temperature change. For Western Europe a standard deviation between 0.2 and 0.5 °C is estimated of which the largest, i.e. 0.5 °C, is used in this study.

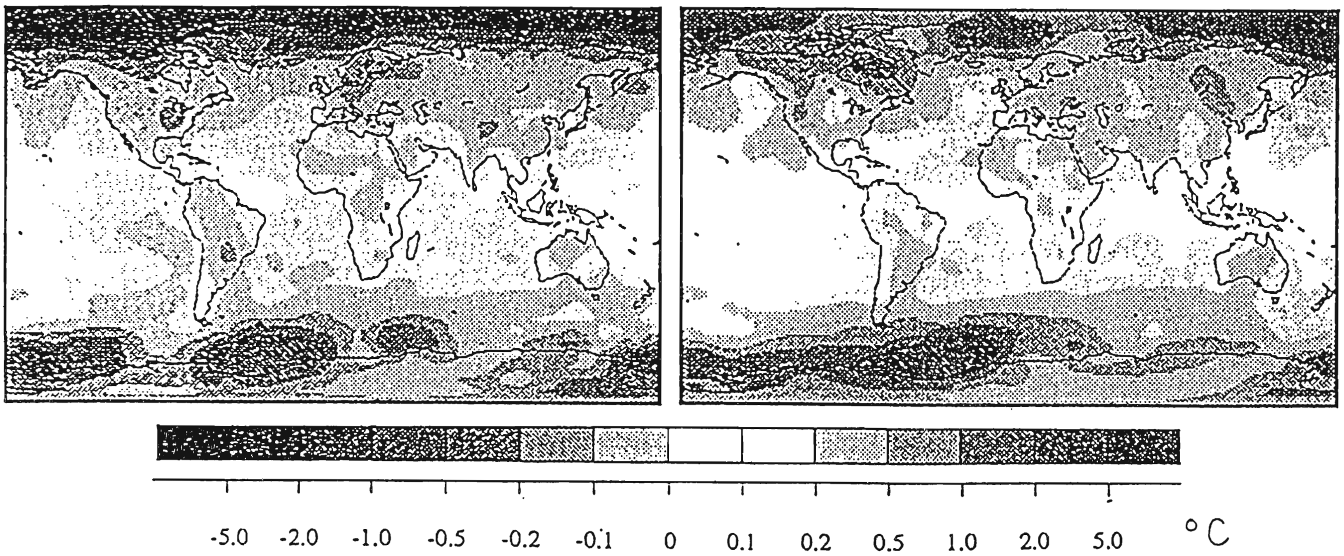


Figure 6.13. Regional distribution of the between-experiment standard deviation of the temperature change (Cubasch et al. 94). This distribution is given for two definitions.

For the latitudinal band at 53N standard deviations of between 0.1 and 1 °C can be found in Figure 6.13, with an emphasis on values between 0.2 and 0.5 °C. The between-experiment variability will probably be less than the variability which is established by performing a single experiment. Indeed, when the mean temperature for the latitudinal band is calculated for each single experiment first, the highest deviations (both positive and negative) will average, resulting in a lower overall standard deviation.

It can be foreseen that the standard deviation for the zonal situation will be higher than the deviation for the global mean value, as on the global scale values for all latitudes will be averaged. These considerations lead to a standard deviation of 0.3°C at 53N, which is higher than the global mean value of 0.2 °C but lower than the value obtained for Western Europe. The results are summarized in Table 6.9.

Geographical scale	σ in °C
Global	0.2
Zonal	0.3
Regional	0.5

Table 6.9. One standard deviation σ due to imperfect knowledge of the initial climatic state.

6.3.4 The-cold start phenomenon

The fact that starting date of the perturbations in the model integrations is not in accordance with what has happened in reality adds inaccuracy to the global warming predictions. The forcing caused by the enhancement of greenhouse gases started around 1800, in the beginning of the industrial revolution. So, the computer simulations should start at this point in time also. However, due to lack in computer capacity, none of the greenhouse scenario simulations which have yet been completed has been able to span this full period of the build-up of greenhouse gases. To limit computer time, the initial state in such global warming simulations is normally taken as an equilibrium state at some time close to the present.

In such an approach, a cold start is introduced, which in reality has taken place in the previous century. The integration assumes the climate is in equilibrium in the starting year of the integration. In reality this is not the case since the climate system in, for example, 1985 is responding to a long history of greenhouse gas forcing. So, the cold start simulation will generally underestimate the climatic change during the first few decades. Then the temperature increase runs parallel with the real increase, but the initially introduced error remains. When the temperature continues to rise, the relative error caused by the cold start decreases with time.

Quantification of the cold start error is of considerable interest for climate predictions for the near future as opposed to long-term predictions. Until this cold start phenomenon is investigated and understood, it is not meaningful to match 'model time' with calendar dates. An attempt to quantify the error introduced by the cold start will be made in the following paragraph.

Methodology

The quantification of the cold start error has been based on Fichefet and Tricot (92) and Hasselmann et al. (93). In both articles estimates of the cold start error are presented for both IPCC-90 scenario A and scenario D. Scenario D assumes stabilisation of the anthropogenic emissions at present day levels. Scenario A, also called the Business-as-Usual scenario, implies a continuation of the actual emission growth. Scenario A gives the best agreement with the emission scenarios used by the coupled GCMs, in which a yearly emission growth of about 1% is imposed. This increase corresponds roughly to the current increase, in terms of CO_2 equivalents. So the results from the calculations based on scenario A have been used for this study.

Fichefet and Tricot assess the influence of the starting date of the model integration on time-dependent projections of greenhouse-gas-induced climatic change with a coupled atmosphere-ocean energy-balance model. Such a model is not as detailed as a GCM, but with this simpler model simulations starting in 1795 are feasible. They have been compared with simulations starting in later years. The simulations have been started in the years 1765, 1900, 1960, 1975 and 1990. Results are given for the simulated surface air temperature changes between 1990 and 2050, i.e. a period of 60 years. In Figure 6.14 the time evolutions from 1991 to 2100 of the simulated warming rate of surface air are presented for the different starting years.

The magnitude of the cold-start phenomenon depends on the rate of forcing change, which depends largely on the emission scenario used and on the oceanic thermal inertia. The slower the forcing increase and the larger the thermal inertia, the stronger the effect. In addition, it depends on the initial state of the computer simulation (Figure 6.14). The largest effect is an adaptation of the calculated temperature increase by 35%. The results indicate that reliable projections of greenhouse-gas-induced climatic change can be obtained if the model integration starts before 1960. For this study, the values of IPCC90-A scenario and starting date 1990 have been used to calculate the cold start error, because this gives the best match with the values used in the GCMs. Averaging the three given values results in a temperature increase which should be 15% higher than calculated by the GCMs considered, i.e. +1.9 °C for CO2 doubling, which do not account for the cold start phenomenon. So this value should be increased by 0.3 °C.

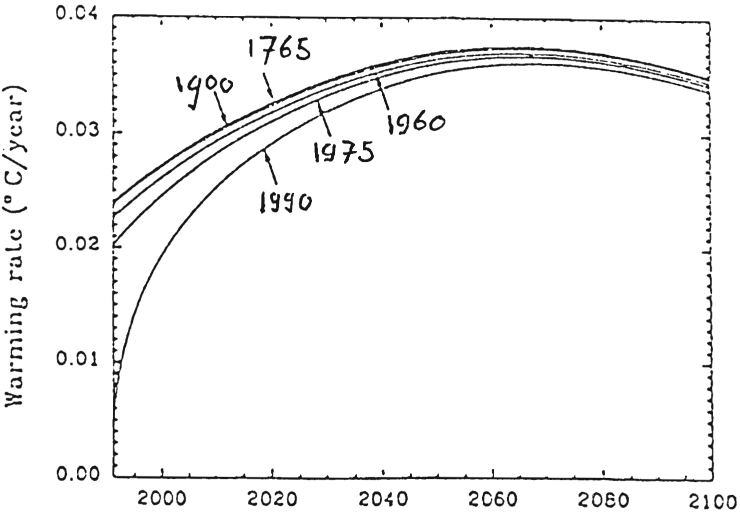


Figure 6.14. Time evolutions from 1991 to 2100 of the warming rate of surface air for the starting years 1765, 1900, 1960, 1975 and 1990 (Fichefet and Tricot, 92).

Hasselmann et al. (93), using another method, derives a general expression for the cold start error. This expression is applied to results obtained with the MPI model by Cubasch et al. (92). For a simulation which uses the IPCC90-A scenario an error of -0.44 °C is found after 60 years, the same period that has been used by Fichefet and Tricot.

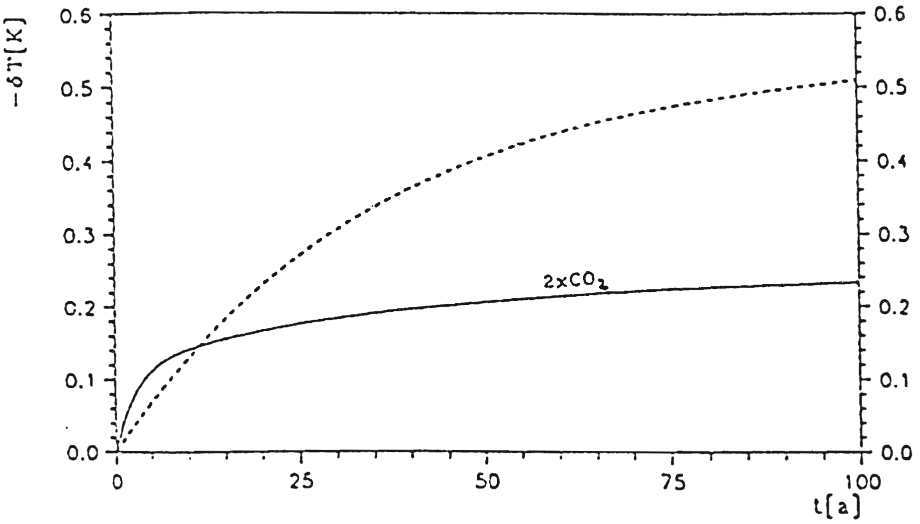


Figure 6.15. Cold-start temperature errors inferred from the "2 x CO2" experiment (solid line) and the IPCC90-A scenario simulation (dashed line) (Hasselmann et al. 93).

Quantitative results on the global scale

The predicted temperature effect for CO2 doubling should be corrected because the cold start phenomenon is not taken into account by the models on which this temperature effect has been based. The cold start error after 60 years is -0.3 °C according to Fichefet and Tricot, and -0.44 °C according to Hasselmann. The advantage of Hasselmann's approach is the use of a coupled GCM which better represents reality. The advantage of the the use of a simpler model by Fichefet and Tricot is that some long climate simulations can be compared with shorter ones. To both results is given equal weight, leading to a rounded underestimation of the temperature of -0.3 °C after 60 years. These results should be put in perspective. Hasselmann gives as a shortcoming of his quantification, which has been obtained with the MPI model in which a CO2 doubling-time of 60 years was imposed, that it has been based on one simulation only. Preferably, the computation should be based on a set of experiments starting from different initial states according to Hasselmann. According to Fichefet and Tricot the build-up of greenhouse gases is not the only climate forcing at decadal- or century-long time-scales. Other radiative forcings like changes in solar irradiance and in aerosols may also be significant. This may lead to a different relative influence of the cold start.
The cold-start errors of the models used can be deduced from Figure 6.16. Three of the four models show a limited warming during the first few decades of the integration; the cold start is barely noticeable in the GFDL simulation (IPCC 92). Because only two values could be found for this cold start phenomenon, leading to low confidence about the accuracy of the quantitative estimate, it has been decided to attribute a similar value to the sigma value associated with this estimate.

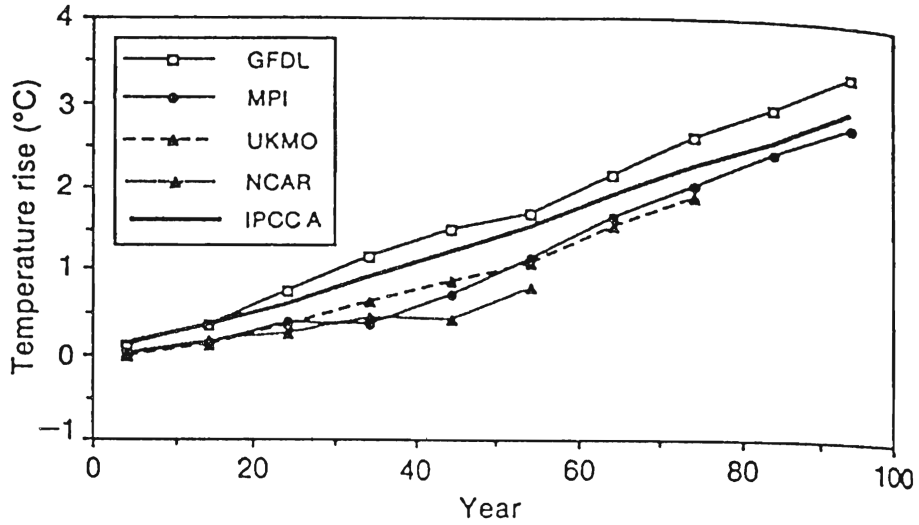


Figure 6.16. Decadal mean change in globally averaged surface temperature in degrees Celsius in various model runs. The cold start error is barely noticeable in the GFDL run.

Quantitative results on smaller scales

Nothing is stated about regional effects of the cold start problem in both studies considered. For this study it is assumed that the anthropogenically induced radiative forcing start everywhere around the globe at the same time. This seems acceptable because most of the radiative forcing since the beginning of the eighteenth century can be attributed to long-lived trace gases like carbon dioxide, nitrous oxide and chlorofluorocarbons (CFCs) of which the atmospheric concentrations are evenly distributed around the globe. In addition it has been assumed that the ocean circulation has had enough time to distribute the changes in temperature, which are due to the fact that the greenhouse effect is not everywhere as strong around the globe because of differences in albedo, solar irradiance, et cetera, evenly around the globe. Based on these two considerations it is assumed that the effect of the cold-start, i.e. the correction on the mean temperature and its associated increase in standard deviation, is everywhere the same quantitatively.

6.3.5 Greenhouse gas emission scenarios

All GCMs use different greenhouse gas emission scenarios. They are presented in Table 6.3 on page 82. These scenarios are all based on assumptions with respect to developments in population, in economic development, in per capita energy use, et cetera. Thus, different emission scenarios account for different societal developments. An overview of scenarios developed by IPCC can be found in IPCC 92. As the rate of greenhouse gas emissions will in the next 100 years most likely differ from any of the scenarios used for the model runs, one may ask what effect a variation in emission rate will have on the calculated temperature increase at a certain point in time in the future. Or, to put it differently: how accurate is the estimate for the time needed to reach a CO_2 doubling. The uncertainty in this estimate, i.e. the timing effect, can be considered as a different expression for the uncertainty in emission rates. Possibly the same temperature increase will be realised with another emission scenario, but at a different point in time. In Paragraph 6.3.5.3 an attempt will be made to give some quantification of this source of uncertainty in the final temperature prediction.

6.3.5.1 Variation in simulated temperature increases

The inaccuracy of the temperature increase at the point of CO2 doubling, caused by uncertainty with respect to future greenhouse gas emission rates, will be addressed in this section. To give an answer on this question, several simulations should be done with the same model. Each of these simulations should use a different emission scenario, while all other parameters are held constant.
The individual simulations should stop at a well defined point in time in the future, say 2050. Then, the temperature increase should be obtained. An analysis can be made about the dependence of the calculated temperature increase on the imposed emission scenario, which in reality is a forcing scenario. Such study, based on runs with a coupled model, could not be found in literature however.
Cubasch et al. (92) use in their time dependent greenhouse warming simulations the IPCC-A and -D greenhouse gas emission scenarios. The point of CO_2 doubling in the latter is not reached during the simulation, which lasted for 100 simulated years.
In Table 6.3 the CO_2 doubling time of the four model simulations is presented. It is clear that it varies from one model to another. For the NCAR simulation it takes another forty year to reach the point of a doubled CO_2 concentration in the atmosphere, when compared with the MPI simulation. Thus, variation exists between the four models with regard to the greenhouse forcing imposed. In other words, part of the standard deviation, due to unfamiliarity with the future greenhouse gas emission scenario, is already included in the standard deviation which originated because of inter-model differences.

6.3.5.2 Timing effect

The uncertainty in the future greenhouse gas emission can also be expressed by the timing effect. When a scenario leading to lower emission is used, more time is needed to reach a doubled carbon dioxide concentration.
The present rate of increase in terms of CO_2 equivalent units is about 1% a year, leading to a CO2 doubling after 70 years. The CO_2 concentration will be doubled after 60 years when the greenhouse gases are emitted according to the IPCC-A scenario, used in the MPI simulation. The emission scenarios used in the other studies are roughly the same as this IPCC-A scenario (see Table 6.3). When the doubling point will be reached when a scenario leading to lower emission rates is imposed, the temperature increase will be larger, because the climate system has had more time to adapt to the changes in forcing. Consequently, in the second case a larger fraction of the equilibrium response will have been established. Note that from the definition of the concept of equilibrium response follows that when emission scenarios leading to the same final concentration of CO2 in the atmosphere will be used, the temperature will be the same.

In reality, the albedo, to take an example, may theoretically decrease for one scenario in which an anthropogenically induced forcing X is imposed, while this may not be the case in the second run in which another forcing scenario is used leading to the same final increase in forcing X. Consequently, the calculated global mean temperature increases may differ. The same can be said about changes in ocean circulation which may possibly be induced by one emission scenario but not by another. These changes may lead to a different distribution of the temperature change if the temperature changes for both emission scenarios are compared.

6.3.5.3 Quantitative statements

Some estimates about the standard deviation due to the uncertainty about the future rates of emission scenarios will be made. It would be easiest to assume that this standard deviation is already included in the standard deviation due to model differences, given in Paragraph 6.2.3. This method can be validated by the fact that the inter-model differences in emission scenarios are not negligible. So, the question is until what extent this standard deviation has already been accounted for in earlier sections.
Cubasch et al. (92) use two different forcing scenarios. Table 6.10 presents the differences between them, as calculated from Figures 6.5 and 6.17. Figure 6.17 indicates when a certain CO2 concentration is reached, according to the IPCC90-A and -D scenarios. For this study, the point in time at which a concentration of 500 ppm will be reached has been chosen as point of reference. Subsequently, the accompanying temperature increase has been obtained from Figure 6.5. The temperature increase for a CO2 concentration of 500 ppm is hard to obtain from Figure 6.5, resulting in a range of values, instead of a single value. For a CO2 increase of about 30 percent, a temperature increase of 0.4 °C is obtained when scenario A is used, while the use of the lower emission scenario D results in an increase of 0.5 °C. The temperature response of the latter is a little larger, as expected. No other results, e.g. of longer model simulations, are available. Only estimates about the difference in temperature increase at the point of CO2 doubling can be made. After 30 % of the CO2 increase the difference is 0.1 °C. Assumed is that this will be 0.3 °C after 100% of the CO2 increase, i.e. at the point of CO2 doubling. Although it is stated before that a percentage of the obtained standard deviation is likely to be already included in the standard deviation arising from difference in model results, this 0.3 °C will be added completely as it is unknown what part has already been accounted for. Consequently, the estimate may be too high.

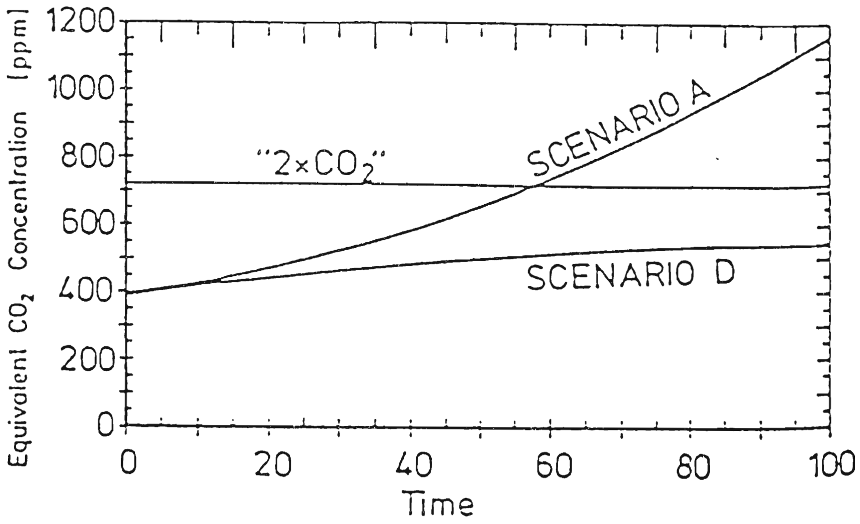


Figure 6.17. Timely evolution of the equivalent CO2 concentration in the IPCC90-A and -D scenarios and a 2 x CO2 experiment (Cubasch et al. 92).

So, the difference in temperature increase between the IPCC-A and -D scenarios is considered to be the standard deviation. Roughly stated, the four models use a forcing scenario equal to the A scenario. When scenario D should be imposed, it takes more time to reach the point of CO_2 doubling, but the temperature increase should be about 0.3 °C higher. When, at the other extreme, the IPCC IS92-E scenario, which assumes high economic growth (IPCC 92), is imposed, the temperature increase may be 0.3 °C lower at the point of CO2 doubling. This point will be reached quite earlier. Consequently, the realised fraction of the equilibrium response is less.
The standard deviation has been calculated from global mean temperature increases. Assumed is that the standard deviation in temperature due to uncertainty about future emission scenarios is the same on the three different spatial scales. This is validated by the fact that the greenhouse gases are distributed evenly.

Concentration of CO_2 in ppm	IPCC-90 scenario A		IPCC-90 scenario D	
	time in years	ΔT in °C	time in years	ΔT in °C
400	0	0	0	0
500	25	0.2 - 0.3	46	0.2 - 0.3
550	34	0.4	100	0.5

Table 6.10. The time needed to reach a certain CO2 concentration and the concomitant temperature increase for two emission scenarios, calculated by the MPI model.

6.3.6 Parameterisation of clouds

GCMs do not contain a real physical description of clouds, but they are parametrized. Furthermore, occurences in the models are based on statistics, i.e. models take decisions like 'No clouds exist, unless saturation occurs; then cloudiness of 95%'. The parameterisation of clouds in GCMs and their relating feedback mechanisms are extremely complex. Models use different approaches to model clouds, making the parameterisation of clouds a major cause of inter-model differences. In addition, when the cloud-feedback parameters need to be established problems arise also in the greenhouse warming simulations.
Two opposed climatic effects due to extra clouds can be distinguished; cooling due to enhanced reflection of solar radiation, resulting from a higher albedo, and warming because there is also more reflection of long wave radiation back to the Earth's surface. The situation becomes more complex when the enhancement of the greenhouse effect is taken into account. Three processes which contribute to the overall radiative effect of clouds, i.e. enhanced cloud coverage, vertical redistribution of clouds and changes in optical properties, are explained below.

1) When temperatures increase, the saturation vapour pressure, which is the maximum possible vapour pressure at a specific temperature, will increase as well, resulting in a lower cloud amount when the water content in the atmosphere is unaltered. Another effect is that surface warming enhances convection, which is vertical transport of air. Convection is a source of cloud formation, increasing the cloud amount. Despite the second effect, GCMs all give a decrease in cloud amount (Cess 90). The sign of the feedback parameter is not known, however, because the clouds have an effect on both the long- and short-wave radiation and it is not yet clear which effect is stronger.
2) A vertical redistribution of clouds will also induce feedbacks. It is generally assumed that high clouds have a net warming effect, while the net effect of lower clouds is net cooling. When the cloud layer is moving to a higher and colder region, the colder cloud layer will emit less radiation and thus have enhance greenhouse warming. The question is whether mean cloud altitudes will change in an enhanced greenhouse climate.

3) Global warming could increase the cloud water content, thereby altering the composition of the clouds which in turn can change the cloud radiative properties. When, for example, the mean radius of cloud droplets decreases in the warmer climate, this will lead to an increase in cloud reflectivity.

list 6-11

6.3.6.1 The uncertainty induced by cloud parameterisation

In this section the change in the standard deviation for the predicted temperature change, due to uncertainties in the parameterisation of clouds, is estimated. The difference between the numerical results given in Paragraph 6.2.3 is for a substantial part caused by this uncertainty. Consequently, a part of the standard deviation that in this section will be determined has been quantified already. An estimate of the remaining part is made based on a study by Cess et al. (90). In this study an intercomparison of cloud feedback processes in 19 GCMs is made (see Figure 6.18).

The climate sensitivity parameter labda λ which represents the global mean temperature increase in relation to the radiative forcing is evaluated for all models; for the globe as a whole and also for "clear" and "overcast" conditions. The enlarged inter-model variation when the clouds are taken into account is made clear by the following results:

clear sky: $\lambda = 0.47 \pm 0.05$ degrees Celsius times square metre per watt (°C $m^2 W^{-1}$)
global: $\lambda = 0.65 \pm 0.26$ degrees Celsius times square metre per watt (°C $m^2 W^{-1}$)

Without clouds the distribution in the parameter as given by the models is 11%. When clouds are included this variation is 40%. Assuming that the radiative forcing is the same in all models, the relative variation in the temperature increase should be the same as that in the sensitivity parameter. Thus an extra uncertainty of 29% is caused by the lack of knowledge about clouds.

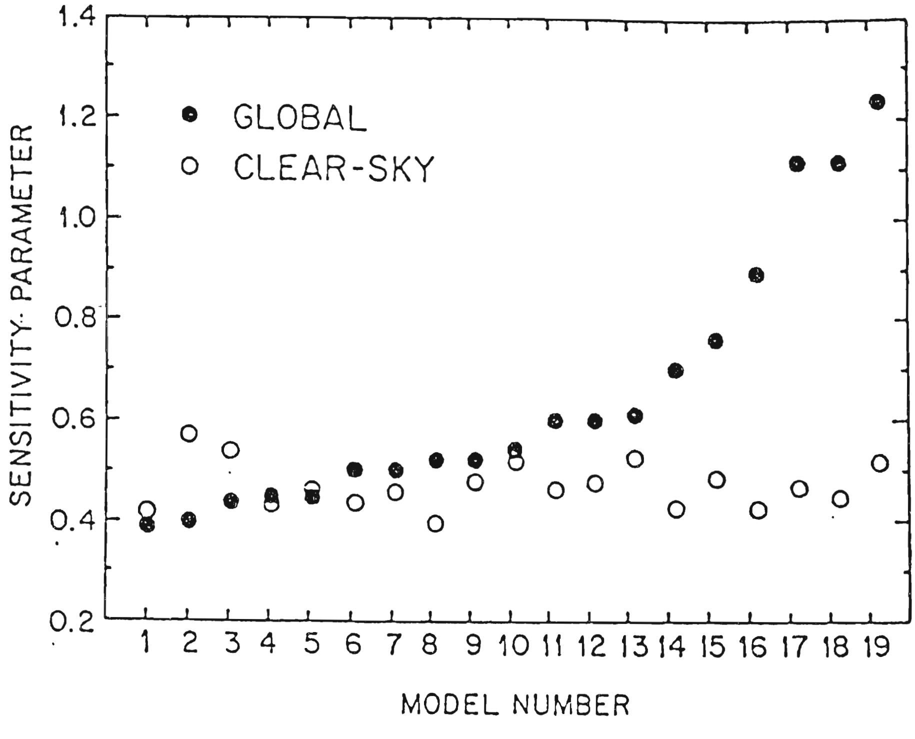


Figure 6.18. Clear-sky and global sensitivity parameters in degrees Celsius times square metre per watt (°C $m^2 W^{-1}$) for 19 GCMs (Cess et al. 90).

6.3.6.2 Quantitative results

Assuming that the global mean temperature increase caused by a doubling of CO_2 is 1.9 °C, the accompanying standard deviation caused by the clouds is 0.55 °C. The question that then should be addressed is what part of this 0.55 °C has already been included in 0.5 °C which originates from inter-model differences. In Cess et al. is stated that cloud-climate feedback is a significant cause of inter-model differences in climate change projections. Referring to this, the assumption is made that half of the 0.5 °C is caused by a different treatment of clouds. This leads to the following conclusions:

- $\sigma_{\text{model variation}}$ is 0.35 °C (equation 6.2) and $\sigma_{\text{uncertainty clouds}}$ is 0.55°C.

On the zonal scale the clouds are treated in the same way. Assumed is that the relative uncertainty about clouds remains the same. This gives the next quantitative results:

- $\sigma_{\text{model variation}}$ is 0.6 °C and $\sigma_{\text{uncertainty clouds}}$ is 0.81°C.

For the regional scale the method results in:

- $\sigma_{\text{model variation}}$ is 0.6 °C and $\sigma_{\text{uncertainty clouds}}$ is 0.64°C.

The quantitative results are summarized in Table 6.11.

	Global scale	Zonal scale	Regional scale
σ clouds (°C)	0.6	0.8	0.6
σ model variation (°C)	0.4	0.6	0.6

Table 6.11. The standard deviation caused by the uncertainty due to parameterisation of cloud processes and the altered standard deviation caused by the model differences as calculated for three spatial scales.

6.3.6.3 Some remarks on the method used

The determination of the standard deviation arising from uncertainty in the treatment of clouds is obtained from the study of Cess et al. (90). In this study the variation in the sensitivity parameter according to the different models is obtained with GCMs. It is assumed that this variation will be the same for coupled GCMs. A similar study like that of Cess should be done with coupled models to verify this assumption.
The global sensitivity parameter has been obtained by Cess et al. with an inverse climatic change simulation. Sea surface temperature perturbations of ± 2 °C were adopted and the respective forcing was reproduced by the models in accordance with the temperature increase. This is exactly the opposite of the 'real' situation, where a temperature change is calculated due to a change in radiative forcing. It is unclear to what extent this inverse approach has influenced the results.

The inter-model variation in the temperature change under CO_2 doubling according to the models used is 26% (+1.9 ±0.5 °C). The atmospheric models calculate a higher percentage, i.e. 40%. This difference of inter-model variance can be explained by the following:

1) The number of coupled GCMs is substantially smaller than the total number of GCMs. An underestimation is more likely with less model results.
2) A comparison has been made between two kinds of models; normal GCMs and coupled ones.
3) A comparison has been made between two kinds of methods. For the coupled model results, the variation in the temperature increase which is caused by a doubling of the CO_2 has been analysed, while for the normal GCMs the variation in the climate sensitivity is considered, obtained with an increase of the sea surface temperature of 2 °C.

list 6-12

To obtain a quantification of the standard deviation caused by the uncertainty with respect to the modelling of clouds a variation of 40% in the value for labda is assumed. This is higher than the value of 26% calculated for the coupled models. As the last value has been obtained with four models only it seems reasonable to use the value of 40% which has been based on a far larger number of models. So, it is assumed that the standard deviation is a certain percentage of the temperature increase and that this percentage remains the same on the three spatial scales. This results in an absolute standard deviation which is smaller for the regional scale than for zonal scale.

6.3.7 Summary of quantitative results

In Section 6.2 the four coupled GCMs have been introduced and their predictions for the temperature increase due to CO2 doubling were given. These values are in themselves not suitable as basis for a probabilistic statement on the future climate. For this, uncertainties which are due to processes which are likely to occur but which have not yet been quantitatively assessed should be accounted for also. This has been done in Section 6.3. If it has been possible to give all these uncertainties a quantification in the form of a standard deviation, a probabilistic statement about the temperature increase in a two times CO2 climate could be given. This statement, then, will consist of a most likely temperature increase, supplemented with the compounded standard deviation expressed in temperature values for sigma.

Source of uncertainty	*Correction* and σ in °C for the global scale	*Correction* and σ in °C for the zonal scale	*Correction* and σ in °C for the regional scale
Natural variability	±0.1	±0.2	±0.2
Man-made aerosols	*-0.4* ±0.3	*-0.4* ±0.4	*-0.4* ±0.6
Initial conditions	±0.2	±0.3	±0.5
Cold start	+*0.3* ±0.3	+*0.3* ±0.3	+*0.3* ±0.3
Emission rates	±0.3	±0.3	±0.3
Cloud parameter	±0.6	±0.8	±0.6

Table 6.12. The deterministically obtained values for the standard deviations, due to different sources of uncertainty.

With all these values, it is possible to calculate the temperature increase and its deterministic standard deviation, according to equation 6.2. Consequently, all these sources of uncertainty are assumed to be independent of each other.

Category of uncertainty	*Correction* and σ in °C for the global scale	*Correction* and σ in °C for the zonal scale	*Correction* and σ in °C for the regional scale
Modelled wisdom	+*1.9* ±0.5	+*2.8* ±0.8	+*2.2* ±0.8
Added wisdom	*-0.1* ±0.8	*-0.1* ±1.0	*-0.1* ±1.1

Table 6.13. The quantification of uncertainties due to model differences and to the fact that the models considered do not account for all processes which are known to influence climate significantly.

For the three different scales the addition of the two categories of information results in:

Global scale:	ΔT = +1.8 ±1.0 °C
Zonal scale:	ΔT = +2.7 ±1.3 °C
Regional scale:	ΔT = +2.1 ±1.4 °C

6.4 Added ignorance

It is acknowledged in this section that there will always remain processes playing a direct or indirect role in climatic change which have not yet been identified or which have only partly been identified. In addition it can also be defended that going from larger geographical scales to smaller geographical scales the amount of physical processes which remain unresolved increases. To allow for both kinds of processes in the probabilistic temperature change predictions or the year 2050:

1) a measure for the enlargement of the standard deviation due to intrinsic ignorance has been estimated, and
2) a measure for the enlargement of the standard deviation due to the transition from larger to smaller geographical scales has been estimated.

In all cases the compensation has been quantitatively estimated as 1.0 °C.

list 6-13

The standard deviations calculated thus far have been obtained in a deterministic way by quantifying all individual uncertain processes. In this section a standard deviation will be estimated which is attributable to processes influencing the atmosphere and, thus, temperature that have not been identified yet. It will also account for processes introducing uncertainty to the simulated temperatures which have been identified, but which can at present hardly be quantified. The 'flux correction' phenomenon (see Paragraph 6.2.1) belongs to this category.

These unidentified and partly identified processes cause an extra uncertainty in the climate prediction. The added standard deviation can be denoted as personalistic, as opposed to derterministic, as there is no way of underpinning the estimate for this standard deviation with quantitative study results. A few phenomenons which can be attributed to the category 'added ignorance' are given:

1) Changes in temperature may alter the chemical equilibrium of the atmosphere. Subsequently, chemical feedback-mechanisms may influence the radiative balance.
2) A vegetation feedback mechanism is not taken into account in the climate models. It is possible that increased temperatures will change the vegetation thereby changing the albedo.
3) It is not sure in an absolute sense that enhanced radiative forcing will increase global mean temperatures. An option is that the averaged temperature remains unchanged, but that the extra energy is used for a change in, for example, the hydrological cycle.

list 6-13

Consequently, the final standard deviation accompanying the temperature increase should consist of two parts. A deterministic part, which is obtained mostly from model results, and a personalistic one, of which the determination of its magnitude is subjective to a large extent. In addition, for the smaller spatial scales a second standard deviation should be added. It is likely that on those scales there are processes which are not essential on the global scale because they average. Consequently, their effects vanish.

6.4.1 A personalistically imposed standard deviation

The standard deviation due to unknown processes in the atmosphere is estimated. This extra quantification is justified by the assumption that scientific knowledge will increase. This will be easily agreed on. Consequently, there are new atmospheric processes or feedback processes to be discovered. The conviction that our knowledge will increase introduces extra uncertainty. This should be accounted for in the predictions. We chose for a standard deviation which is equal in value to the deterministically obtained standard deviation on global scale presented in Section 6.3; i.e. 1.0 °C. This choice is admittedly arbitrary. In order to present more accountable estimates, it would probably be worthwile to study the historical evolution of the applied uncertainty ranges with respect to the simulated temperature for a two times CO2 climate. However, at present this is beyond the scope of our study.

6.4.2 The standard deviation imposed on the results for the smaller scales

On the smaller, zonal and regional scales the added ignorance consists of the personalistic standard deviation, given above, completed with a standard deviation which arises from uncertainties playing a role on smaller scales only. Such extra uncertainty is introduced by the transition from the global to the zonal scale and by the transition from the zonal to the regional scale. An example of an atmospheric process that becomes important on smaller scales is advection. In Western Europe there is much advection from warm air, coming from the Atlantic Ocean. On this regional scale, advection has its influence on the temperature. On global scale however, this regional effect disappears, because on average, the regions which have a warming effect of advection, will be about equal in number to the regions which have a cooling effect becaused advection transports the heat to cooler places. These extra sources of uncertainty should be quantified. Chosen is for the value of 1.0 °C, both for the transition both from the global to the zonal scale and from the zonal to the regional scale. Again, this choice is purely personal. The values obtained will be added to the deterministic standard deviation, being a combination of all standard deviations obtained in the previous section, with use of equation 6.2.

Added categories of uncertainty	**Global scale**	**Zonal scale**	**Regional scale**
Personalistic σ	±1.0	±1.0	±1.0
Added σ; transition global to zonal	-	±1.0	±1.0
Added σ; transition zonal to regional	-	-	±1.0

Table 6.14. Summary of all standard deviations obtained, given in degrees Celsius (°C).

Category of uncertainty	*Correction* and σ in °C for the global scale	*Correction* and σ in °C for the zonal scale	*Correction* and σ in °C for the regional scale
Modelled wisdom	*+1.9* ±0.5	*+2.8* ±0.8	*+2.2* ±0.8
Added wisdom	*-0.1* ±0.8	*-0.1* ±1.1	*-0.1* ±1.1
Global ignorance	±1.0	±1.0	±1.0
Zonal ignorance	-	±1.0	±1.0
Regional ignorance	-	-	±1.0

Table 6.15. The quantification of uncertainties due to model differences, to the fact that the models considered do not account for all processes which are known to influence climate significantly, and to the fact that there are still some processes influencing climate which have yet to be discovered.

For the three different scales the addition of the five categories of information results in:

Global scale: $\Delta T = +1.8 \pm 1.4$ ˚C
Zonal scale: $\Delta T = +2.7 \pm 1.9$ ˚C
Regional scale: $\Delta T = +2.1 \pm 2.2$ ˚C

6.5 Final results

Under the assumption that the temperature changes, as calculated by the coupled models considered for this study, comply with a Gaussian distribution, and that all additional processes, which significantly influence the climatic system but which are not yet incorporated in the models, have been accounted for in this study, the temperature change averaged over the decade centered around 2060 with respect to the averaged temperatures for the decade centered around 1990 will, for the three spatial scales considered, be as follows:

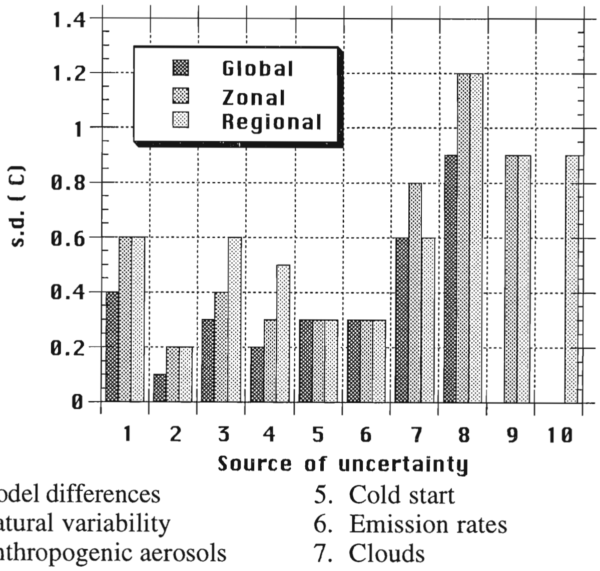
Global scale:	ΔT = +1.8 ±1.4 °C
Zonal scale:	ΔT = +2.7 ±1.9 °C
Regional scale:	ΔT = +2.1 ±2.2 °C

It should be noted that for a quantification of the temperature increase in 2060 which is due to the enhancement of the Greenhouse Effect, the temperature increase which already has occurred in 1990 should be added to the values given.

list 6-14

All standard deviations obtained are summarised in Table 6.14 and Figure 6.19. Under the assumption that the temperature distribution is Gaussian, the temperature changes, including the associated standard deviation (one sigma), can now be given:

Global scale:	ΔT = +1.8 ±1.4 °C
Zonal scale:	ΔT = +2.7 ±1.9 °C
Regional scale:	ΔT = +2.1 ±2.2 °C



legend:

1. Model differences
2. Natural variability
3. Anthropogenic aerosols
4. Initial conditions
5. Cold start
6. Emission rates
7. Clouds
8. Added ignorance
9. Added gl-zon
10. Added zon-reg

Figure 5.19. The standard deviations of all sources of uncertainty for three geographical scales; the global, the zonal, i.e. around 53 degrees Northern latitude, and the regional scale, i.e. in Western Europe.

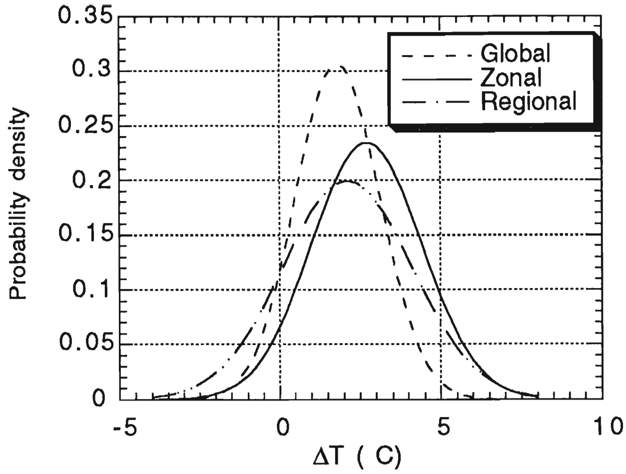


Figure 6.20. Normal distribution for the temperature increase for three geographical scales; the global, the zonal, i.e. around 53 degrees Northern latitude, and the regional scale, i.e. in Western Europe.

The normal distributions of these temperature increases are presented in Figure 6.20. It shows that negative temperature changes are possible also; an artefact of the mathematical method used. Figure 6.20 shows that the probability is 68% that the temperature increase in the Netherlands will lie in the range between 0.1 and 4.1 °C at the time of CO2 doubling, i.e. after about 70 years.
The probability of the climatic change is presented in a different form in Figures 6.21 and 6.22. The probability that the temperature change after, say, 60 years is at least the corresponding value given can be deduced from the figures. For example, Figure 6.22 shows that the probability is 2% that the temperature increase in Western Europe will be about 5.4 °C or higher after 60 years. The two figures are based upon the temperature increase and its standard deviation at the CO2 doubling point. The temperature is assumed to increase linear, the standard deviation during the presented years also, be it at another rate. Although these figures are not highly accurate, they give a clear picture of the temperature increase that may be expected.

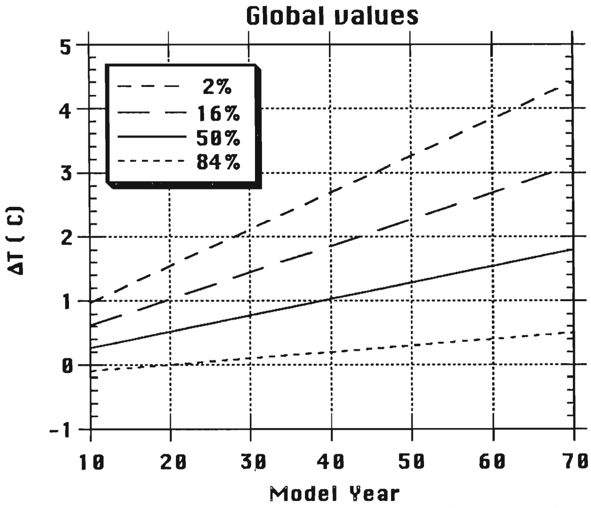


Figure 6.21. The probability of a global temperature change of at least ΔT degrees Celsius over so many years from the decade centered around 1990.

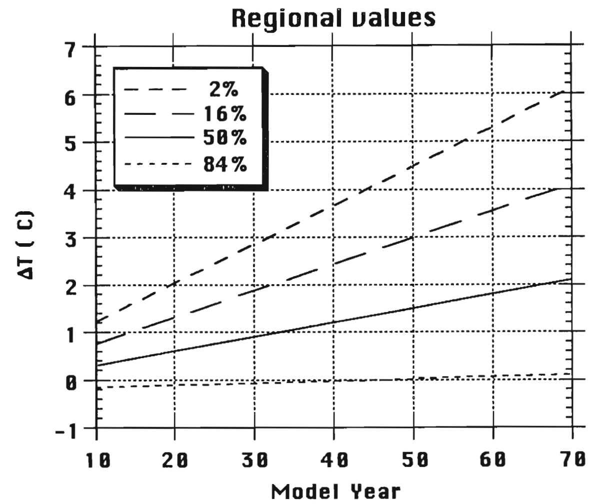


Figure 6.22. The probability of a temperature change in Western Europe, which includes the Netherlands, of at least ΔT degrees Celsius over so many years from the decade centered around 1990.

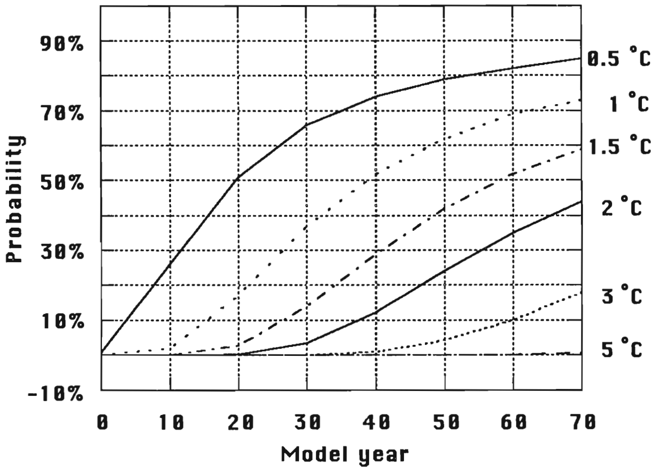


Figure 6.23. The probability that the Earth will have warmed by at least so many degrees Celsius (vertical axis) so many years from now (horizontal axis).

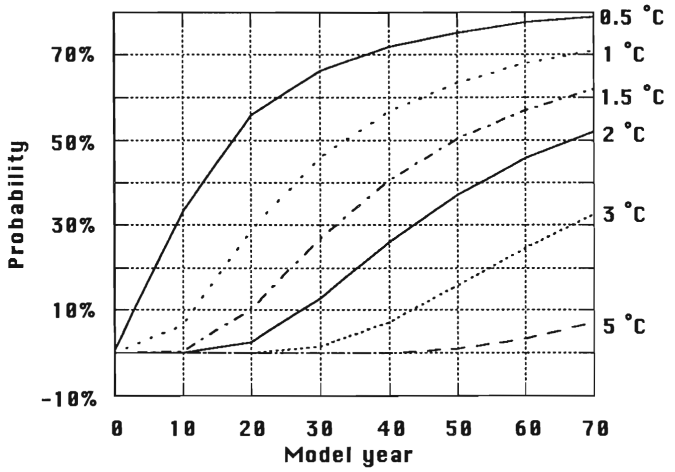


Figure 6.24. The probability that Western Europe will have warmed by at least so many degrees Celsius (vertical axis) so many years from now (horizontal axis).

6.6 The palaeo-analogue Method

The palaeo-analogue method:

1) can be used to enhance the confidence in the regional distribution of the global warming as predicted by other methods,
2) should be used with some caution because forcing mechanisms in the past may have been different from current and future forcing mechanisms, and
3) indicates that the sensitivity of certain regions to a globally averaged temperature increase agrees well with the sensitivities as obtained from model results.

list 6-15

In the previous sections a probabilistic prediction for the climatic change in the middle of next century has been obtained with as basis the results from coupled GCMs. Predictions for the temperature change due to increases in CO2 can also be based on results from the palaeo-climatologic discipline. One of the palaeo-climatological methods which can be used for this is the palaeo-analogue method. In this section, this method will first be described shortly. Some quantitative conclusions following from palaeo-climatologic considerations will be given also. Then some attention will be given to the comparison between the results which have been calculated in the previous sections and those obtained with the palaeo-analogue method. Finally, some conclusions will be given which may either strengthen or weaken the probabilistic results which have been presented above.

6.6.1 Description of the palaeo-analogue method

This method has two distinct and rather independent parts. The first derives an estimate for sensitivity of the global temperature on atmospheric CO2 concentrations. This estimate will be based on estimates of CO2 concentrations at various times in the past and the corresponding global average temperatures, adjusted to allow for past changes in albedo and solar constant (the average flux of the solar irradiance). Then, regional patterns of past climates are reconstructed for selected past epochs from palaeo-climatologic data. As will be shown some of them may be considered as analogues for future climates under enhanced greenhouse conditions.
A vast array of techniques have been used to reconstruct past climates. For example, work on land involves examination of glacial moraines, pollen and lake levels. The reconstruction of events has been greatly aided by radiocarbon age dating.

Estimate of global temperature sensitivity

Three periods from the past have been suggested as analogues of a future warm climate. These are as follows:

The Pliocene climatic optimum;	3,300,000 to	4,300,000	years BP
The Eemian interglacial optimum;	125,000 to	130,000	years BP
The Mid-Holocene climatic optimum;	5,000 to	6,000	years BP

Longer ago, there have been many more of such warmer periods, for example the Cretaceous, 100 million years ago. What makes the Cretaceous attractive for climate modellers are the high estimated CO2 concentrations, so in that case it is comparable for a future enhanced greenhouse climate. Estimates of a concentration 10 times that of present concentration have been made (Crowly 91).

However, during the Cretaceous the land-sea distribution was quite different compared to the current situation. The solar constant is likely to have been significantly lower than today too. These and other factors make the Cretaceous significantly different in character compared to the present period or the foreseeable future. So data from the Cretaceous will not be used for comparison.
Reconstruction shows that the three above mentioned climates were considerably warmer than the modern climate. Atmospheric carbon dioxide concentrations in the Pliocene optimum are estimated to have been near 600 ppm, i.e. about twice the pre-industrial value. In the Eemian and Mid-Holocene the concentration was a little bit higher than the pre-industrials value. A direct and univocal proof that the temperature increases in the past were caused by increases in CO2 concentrations does not exist however. From historical records is known that on larger time scales the changes in the temperature might even lag changes in the CO2 concentration. In Figure 6.23 the trend of both parameters for a period of 160,000 years is shown. More arguments that these past climates cannot be used as analogues for future greenhouse warming can be found.

For a climate in the past to be a detailed analogue of the future climate under enhanced CO2, it is necessary that the forcing factors and the boundary conditions are similar. It is possible that this forcing in the past was the changed seasonal distribution of incoming solar radiation. This may not necessarily produce the same climatic change as a globally-averaged increase in greenhouse gases. Further, because future temperatures will increase relatively fast, an unique combination of a warm atmosphere with polar ice-sheets will occur, a condition far different from warm periods in the past.

Regional response to global warming

The palaeo-analogue method has been used to reconstruct regional patterns of climate for three periods, i.e. the mid-Holocene, the Eemian and the Pliocene. Although the nature of the forcing during these periods was different, the relative values for the mean latitudinal temperature change in the Northern Hemisphere were similar for each epoch. Thence, these epochs are regarded as analogues. This may lead to the conclusion that the general circulation adjusts itself to give a similar response to different forcings. The considerable similarity between the temperature anomaly maps suggests that the regional temperatures are, to a first approximation, directly proportional to increasing mean temperature (see Figure 6.24). If this is true, then the reconstruction of the past climates can provide relatively reliable estimates of spatial patterns of future climate change.

6.6.2 Uncertainties in the palaeo-climatology

When the palaeo-analogue method is used, there are uncertainties associated with the interpretation of the reconstructions. The problems include imprecise dating of the record as well as interpretation of the effects of equilibrium versus non-equilibrium conditions:

1) For dating of record radiocarbon age dating is used. As might be expected, this method has no absolute accuracy. For example the dating of the last glacial maximum (22,000 - 14,000 BP) has a precision in the order of 1,000 years.
2) The increase of CO_2 is a non-equilibrium process. it is time dependent due to the continuous emission of greenhouse gases. It is possible that changes in the past were caused by abrupt transitions in, for instance, CO2. If the CO2 concentration from that moment on remains stable, then the establishment of a new climatic situation should be considered as an equilibrium processes. In comparing such different processes to each other extra sources of uncertainty arise.
3) Various other non-CO2 forcing factors have caused the past climatic changes.
4) Data are highly unevenly distributed over the globe with relatively few measurements at oceanic sites. In many continental regions there is an absence of data also.

list 6-16

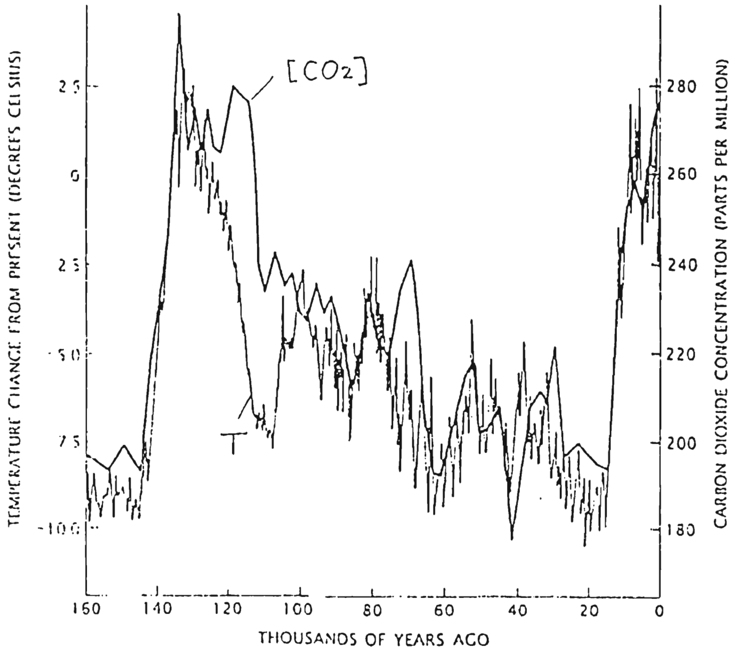


Figure 6.25. The correlation between temperature and CO2 in the atmosphere over the past 160,000 years (Visser 92).

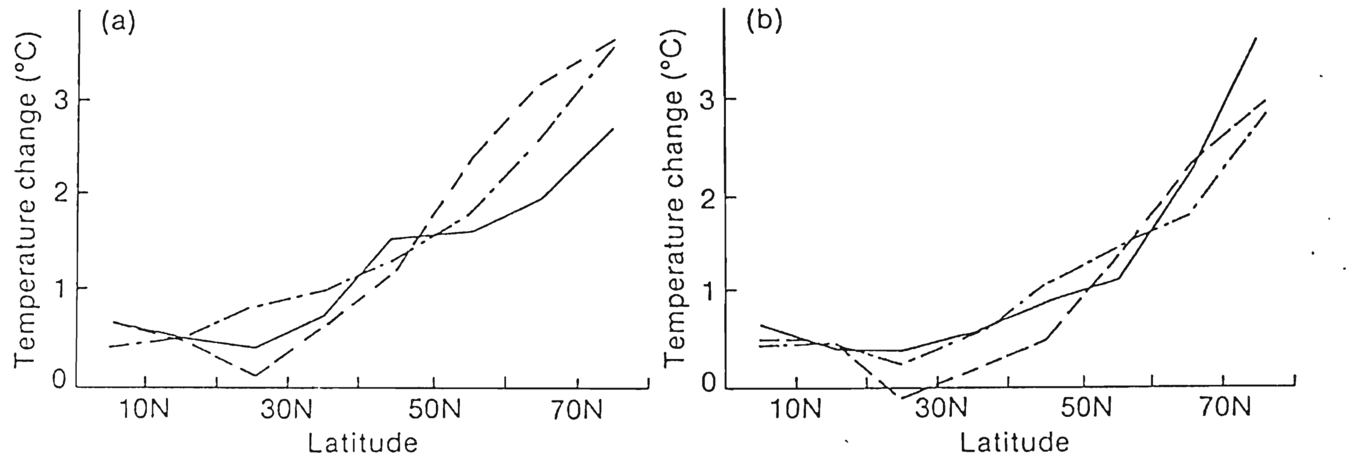


Figure 6.24. Relative temperature changes at different latitudes of the Northern Hemisphere during the palaeo-climatic warm epochs; (a) winter, (b) summer. Full line: Holocene, dashed line: Eemian, dash-dotted line: Pliocene (IPCC 90).

6.6.3 Comparison of GCM-results with results from palaeo-climatology

Nonetheless their associated uncertainties palaeo-climatologic results will be used as a test for the results obtained in earlier sections. As stated above, reconstruction of three warm epochs in the past lead to similar regional distributions, especially when the seasonal temperature anomalies are scaled with the mean Northern Hemispheric temperature anomaly (Shabalova and Können 95). This similarity exists despite the existence of other, non-CO2 forcing mechanisms in those past periods.
A remarkable conclusion from the model results is the relatively small temperature response in the North Atlantic (Paragraph 6.2.2.2), which is caused by the decreased strength of the thermohaline circulation. In the palaeo-analogue study by Shabalova and Können this area is given special attention also. In is found that the North Atlantic climate is characterised by poor agreement between the different warm epochs, resulting in a large standard deviation for the area. Other records show that this particular region is characterised by a high climatic instability which can be represented by two modes.

A cold mode in which the thermohaline circulation is de-activated, and a warmer mode with an active circulation in which the Gulf Stream brings warm water to the higher latitudes. Note that the cold mode should not be mistaken for a weaker thermohaline circulation. Thus, this specific region is very difficult to predict. This also counts for the land areas which are influenced by this specific region like Scandinavia (which has the largest standard deviation resulting from this effect) and the region of interest for this study, which includes the Netherlands.

Quantitative results

The palaeo-climatic result is a sensitivity of about 3.0 °C for CO_2 doubling (IPCC 90). The present study gives a global mean temperature increase of 1.8 ± 1.3 °C at the point of CO_2 doubling. Because this value is about 60% of the equilibrium response, as calculated in Paragraph 6.2.6, this should result in a temperature increase of 3.2 °C. Below it will be analysed whether there is the same overlap amongst the palaeo-climatologic and model results on the smaller scales. In Shabalova and Können (95) a mathematical equation can be found from which the warming on a certain latitude relative to the global mean warming, based on palaeo-climatologic results, can be calculated. It is represented by equation 6.3.

$$dT / \Delta T_g = 3.21 \sin^4(\varphi) + 0.36 \qquad \text{(equation 6.3)}$$

For the the Netherlands, the value of φ is 53°. With equation 6.3 can be calculated that the temperature increase on the 53th latitude should be about 1.7 times the global mean temperature increase. Model results give a factor of 1.5, so a fairly good agreement has been found.

In Shabalova and Können (95) the scaled temperature changes are given for some regions also. For Europe (45-60N, 0-40E) these are:

Palaeo-winter:	1.0 ± 0.5 °C
Palaeo-summer:	1.4 ± 0.4 °C

This scaling is done with $\Delta T_{NH(land)}$, not with ΔT_g. The former is about 1.2 times the latter for the three periods in the past, resulting in too low values when compared with the model results. Calculating the mean of those two values gives 1.2. In other words, based on the results from the palaeo-climatologic discipline, the temperature change in a region accomodating the Netherlands should be about 1.2 times the global mean temperature increase. This factor is the same as that based on model calculations. According to the results obtained with the palaeo-climatologic method, the regional temperature increase is lower than the zonal temperature increase. This can be explained with the influence of the northern part of the North Atlantic, which had in some periods in the past a negative influence on the temperature increase in the region of interest. Table 6.14 makes clear that although on smaller scales the accuracy becomes somewhat less, the palaeo-climatic results concerning the distribution of the temperature increase agree fairly good with the model results.

	$\Delta T_{regional}/\Delta T_{global}$	$\Delta T_{zonal}/\Delta T_{global}$
Coupled models	1.2	1.5
Palaeo-climatology	1.2	1.7

Table 6.14. Comparison of model results with palaeo-climatic results.

Concluding remark

It should be stated that the palaeo-climatologic method deals with equilibrium situations, while the model results used are from time-dependent simulations. When the factor $\Delta T_{regional}/\Delta T_{global}$ is not changing in time, this difference in approach does not matter. When this factor is varying, however, one should take care when comparing the determination of the regional patterns from palaeo-climatologic results with those from model results.

6.7 Discussion of the results

The method to supply quantitative probabilistic statements on climatic change as proposed in this chapter can be used in a risk approach, provided that the conditionality of the method is stressed.
The results which follow from a case study, which has been based on this method, and which have been presented in this chapter also, are probably less suitable for use in a risk approach as they do not deal with the climatic changes from which the largest societal impacts may be expected.

An alternative method for the calculation of quantitative probabilistic results on climatic change has been presented. Its characteristics are that it is a relatively simple and transparent method by which an enormous amount of information of both theoretical and technical origin can be combined. New information can easily be integrated by the method, the consequence of which is that the results can be updated fastly. The results can be visualized in many palpable ways, according to the taste of the user.

6.7.1 Analysis of the results

To put the results of the method into perspective some remarks about the conditionality of the method should be made.

Amount of data used. For the quantification of many sources of uncertainty, including the uncorrected model prediction for the global mean temperature at the point of CO2 doubling, not many data could be found and, thus, used. In the most positive cases the quantifications were based on results by four independent studies only. Partly due to the calculation method used this has led to a strong enlargement of the 95% confidence intervals.

Assumed distribution of the data used. For all identified sources of uncertainty for which data were available it was assumed that the distribution of the data did comply with a Gaussian distribution. In other words, the distribution of the data found has not been analysed. If this will be done in the future it may well turn out that the distribution of the data is more in accordance with other distributions as known from the statistical discipline. At the same time, it should be acknowledged that there are too few data to attribute a well-known distribution to the data found. So, an analysis in the future is only feasible when more (model) output is available. If this distribution will finally be established the question should be addressed whether there is any reason to assume that a perturbed climatic system will comply with a distribution which is based on either past data or model output. This uncertainty with respect to the distribution of climatologic data which will occur in reality, which is largely intrinsic because it applies to a situation which cannot be observed, justifies to a large extent the choice for a Gaussian distribution. There is as much reason to opt for a Gaussian distribution as there is reason to choose for any other distribution, manifest unrealistic distributions barred.

Implications for the smaller spatial scales. Data found apply to larger scales only. Consequently, for the smaller scales these data had to be adapted in a certain way. In some cases this has been done subjectively. In all cases this led to an enlargement of the confidence levels for the smaller scales. Secondly, for many sources of uncertainty no quantifications could be found. These had to be estimated subjectively. In addition, because the larger models, of which the results have been used for this study, do not resolve smaller-scale physical processes extra enlargements of the confidence level for the transition from global to zonal scales, and from zonal to regional scales were imposed. Combination of all three processes leading to enlargement of the confidence levels leads to the situation that the width of the confidence levels for the smaller scales is primarily determined by subjective quantitative estimates for the respective sources of uncertainty.

Implications for impacts. While the topic of 'impacts of a climatic change' has not been dealt with specifically in this report it may be anticipated that the results of this study are of particular interest to impact scientists. Due to the applied methodology extreme deviations from the most likely climatic change are presented as being plausible options, while the emphasis on the most likely change is relatively weak. This emphasis on extreme climatic changes is not confirmed by results from other quantitative probabilistic methods. Acceptance of the realism of this artefact of the methodology applied follows the acceptance of this methodology as a whole as a sound way for assigning probabilities to future changes in the climate.

6.7.2 Feasibility of a risk analysis based on the results of the case study

The question whether the results presented in this chapter can be used for a risk analysis -or an opportunity analysis for that matter- cannot readily be answered. There are two reasons for this.

First of all, the question should be addressed what the objective is of the risk analysis. This question will be elaborated on in the following section which presents the discussion and conclusion of the complete study, of which the case study which is presented in this chapter forms a part only. At this point it suffices to say that the risk approach which has been advocated by the initiators of the study has not been defined to the extent required, and that there will be a large difference in approach when the objective is to create a large basis among the general public for measures to be taken compared to the situation when the objective is to find a basis for calculating the macro-economic costs of (mitigating or adapting to) a climatic change.

Secondly, quantitative probabilistic estimates about future temperature do not generally visualize risks. By this we mean that temperature change by itself is not considered as a risk. This is especially true if risks are considered from a purely anthropogenic standpoint; man is probably very well able to adapt itself to changing temperatures. This may lead to the conclusion that information is needed about the kinds of risks that should finally have to be determined. If this information asks for an accurate assessment of extreme temperature events in the future, then the information presented in this chapter is probably not very well suited. The method was used to consider changes in mean temperature, and by including the quantification of standard deviations for many uncertain processes it leads to a broadening of the distribution of plausible temperature changes. While this leaves the possibility for enormous changes in mean temperature open, though with small associated probability, it creates interest in changes in the occurrence of weather extremes at the same time. However, while for the study of impacts and, thus, of risks of utmost importance, the method as it has been used in this study does not give any information about changes in this occurrence. Indeed, it can be doubted whether the probabilities calculated for large deviations of current mean temperatures can be used as a basis for the estimation of changes in the occurrence of extreme events. This is due to the fact that a Gaussian distribution was assumed for all calculations while it may well be so that the distribution of realisations which may occur in reality does not comply with a Gaussian one.

This leads to the following conclusions. The results from the underlying case study, for instance the 2.5 and 97.5 % percentiles of the change in global mean temperature for 2060, are defensible to a large extent. Assumptions are inherent to the method proposed. They should be made explicit for a good interpretation of the results. The five main assumptions which led to the results above are:
1) The temperature output as provided by the coupled models considered for this study, is assumed to be representative for the current state-of-the-art knowledge with respect to perturbations of the climatic system.
2) The most important processes, which influence the temperature response of the climtic system to perturbations but which have not yet or only partly been accounted for in the models, have all been quantitatively estimated in this study in an adequate way.
3) The quantitative subjective estimate which has been applied to the adapted model results to account for our persistent, but decreasing lack of technical knowledge is of the right order of magnitude.
4) The uncertainties which are introduced by the transition from larger to smaller geographical scales have been quantitatively estimated in an adequate way.
5) All processes which may influence future temperatures on the three geographical scales considered in this study are accounted for by the final estimate.

The method may provide information about the behaviour of climatologic variables in the future in a probabilistic sense. Because both lack of theoretical knowledge and inadequacies associated with the process of numerical modelling are quantified by the method, upper and lower quantitative probabilistic estimates can be generated for the future state of any climatologic variable. Increasing knowledge may then lead to a decrease of the range between the lower and upper estimates. In this respect, the method proposed can be considered as valuable.
The output of the method which is presented in this chapter is probably less useful for use in a risk approach, because it does not concern changes which are associated with the large societal risks of a climatic change. For use of the method in a risk analysis, the focus should be either on other climatologic variables or on other statistical representations of a specific variable. For instance, to calculate changes in extreme events the statistical treatment should not be concerned with the yearly averaged temperatures based on decadal means but rather on direct model output which refers to daily mean temperatures on different spatial scales.

DISCUSSION AND CONCLUSION

Introduction

This project has, first of all, been set up as a feasibility study aimed at addressing the question whether it is possible to provide accountable quantitative probabilistic statements on climatic change for a specific area at a specific point in future time. Based on the results of the project the answer should be a firm 'yes' with a firm 'but'. The positive answer refers to the methodologies identified and the presentation, in Chapter 6, of an additional methodology. The restriction which accompanies the affirmative answer refers to the fact that each method, which is developed within one of the methodologies identified, is based on different conditions -the probabilistic statements provided are thus conditional- and that each method addresses a different question.

Here, the appraisal of the probabilistic methods identified and the probabilistic statements provided in this report, will be dealt with. It is hoped that the discussion presented will indicate which probabilistic method is most suited for use in any of the many subdisciplines of the study of climatic change. Questions that will be addressed are:

1) which probabilistic methodology provides the most appropriate information when the aim is to produce the most accurate climatological results,
2) which probabilistic methodology provides the most appropriate information when the aim is to produce results which can be used for impact studies,
3) which probabilistic methodology provides the most appropriate information when the aim is to produce results which can be used by policymakers in order to inform the general public and, thus, influence the public support for measures to be taken,
4) what is the value of the results from an alternative methodology, presented in Chapter 6 of this report, and
5) what kind of research should be done to provide probabilistic statements which can be used for the tasks mentioned under 1, 2 and 3.

Before these questions will be addressed some provisions should be made explicit. First of all, it should be acknowledged that it is possible to give quantitative probabilistic statements on the future climate. This result may seem unexpected to climatologists who have fundamental theoretical knowledge about the predictability of climate, but has everything to do with the following remark.

Secondly, all probabilistic statements which apply to real life situations are conditional. So for a sound interpretation of probabilistic results it may pay to inform oneself about the conditions.

Thirdly, it should be made clear that the question about how climate will behave in the future requires that a climatic forecast should be given rather than a quantification of the expected climatic change. A climatic forecast gives an indication of what the temperature, inter alia, will be at a certain point in the future, e.g. 20 °C in 2060, while an quantification of the climatic change will present the change in mean (or other) values only, e.g. 2 °C in 2060. From the last kind of information cannot be deduced what the actual climate will be in the future, mainly because a quantification of climatic change excludes by definition the natural variability of the climate. In this study an attempt to give a climatic forecast has been made.

The fourth point is that the above questions should be addressed from the perspective of a risk-analysis. This provision has several consequences, as has been explained in the text, one of them being that the concept of climate should be considered on relatively small geographical scales only.

How to produce the most accurate probabilistic climatological results?

Here, the aim is to obtain the most accurate probabilistic climatic forecast in the sense that it has the highest resolution in space and time and that it is based on a model which mimicks the characteristics of the climatic system in a theoretical and practical sense most accurately. These demands lead to the conclusion that some models are better suited to produce probabilistic statements than others.

For accountable results the model output should be based on a mathematical description of the dynamical processes playing a role in the climatic system. Only then can model output be attributed to changes in fundamental physical processes. This is important because it is the only method to give confidence when the deterministic paradigm is followed, which in this context reads like "the effect we observe or predict can be explained from physical considerations". This faith in physics can also be accounted for by the fact that the mechanisms forcing the climate, now and in the future, are to a large extent different from forcing factors in the past. For example, present forcing mechanisms comprise significant increases in tropospheric and stratospheric aerosols, significant increases in tropospheric ozone and significant decreases in stratospheric ozone, and significant increases in the atmospheric concentrations of many other greenhouse gases, of which some are also chemically reactive, like nitrogen oxides, methane and chlorofluorocarbons. Another example is changes in land use; these may also be important forcing factors on regional scales. The fact that so many climatic forcing factors deviate substantially from past forcing factors make that it can be considered as unsound to base predictions on relations which have been established in the past, e.g. between temperature and atmospheric carbon dioxide concentrations. The same counts for impressive correlations for which no physical mechanism exists, e.g. the correlation between temperature and the solar cycle length. From one perspective one should defend that they should not be dismissed from the start, because an explanation may some day show up. However, they should not be used as explanation for climatic changes either, because there is no reason to assume that the correlation will hold.

Another reason to demand a physical description of the underlying processes is that the climate can be strongly non-linear. This characteristic of the climate cannot be mimicked by linear models, like for instance the regression models considered in this study.

This leads to the conclusion that physical climate models, be it the simpler 1-D energy-balance models or the more complex coupled 3-D General Circulation Models, are the most appropriate tools if the aim is to produce the most accurate results.

If we have decided to use physical climate models we may still ask whether all meteorological output is equally reliable on smaller spatial and temporal scales. It can be imagined easily that for a meteorological variable which shows a relatively small variability, e.g. temperature, the output is more reliable when going from global to regional scales, than for a variable which shows a large variability, e.g. precipitation. This is indeed the case. Predictions for many variables have to be classified as less reliable, mainly because climate models are unable to reproduce their current distribution in both space and time giving little confidence in simulations of future patterns. It can be said that only the first derivative of changes in forcing, i.e. temperature changes, can be calculated with both high accuracy and confidence.

In addition, if it is required that a timing is associated with the climatic changes then the focus should be narrowed to those models which are able to perform time-dependent simulations, i.e. simulations of the timely evolution of a climatic change. At present and under the condition of global coverage with relatively high spatial resolution, only the coupled 3-D General Circulation Models are able to do this. Note that this point implicitly addresses another issue which should be resolved, i.e. whether the objective is to give a long-term climate forecast or a quantification of the anthropogenically induced climatic change. When this question is put in the context of a risk analysis the answer should be the former, because only a climate forecast attempts to describe the exact climatic situation some years hence. However, this requires an extra effort as individual processes which determine the natural variablity, like volcanoes and ENSO phenomena, will have to be modelled in some way, probably stochastically.

How to produce results which can be used for impact studies?

If the aim is to produce quantitative probabilistic statements for impact studies then the emphasis should be specifically directed to those meteorological variables for which changes -in intensity, in frequency of occurrence, or in some other statistic- are expected to have a large societal impact. This may lead to more attention being given to precipitation changes and less to temperature changes when impact on agricultural output is considered, to give an example. Partly depending on the impact which is studied, e.g. impact on human health or on crop yield, impact studies require often meteorological data for a specific location and with a relatively high temporal resolution. In general this will be at the expense of the predictive skill and, thus, the reliability of the output.

For the assessment of what kind of changes in which specific meteorological variables should be studied, the input should come from impact scientists. They should indicate what changes in which variables are of most importance with respect to their impact, however defined. Another point that should be addressed by impact scientists -and it is felt strongly that this point is often overlooked- is what kind of changes should be addressed by climatologists; i.e. which statistical representation of climatic changes is best suited for use by impact models. For example, it can be imagined quite easily that impact scientists are more interested in changes in the seasonal distribution of, and in run events regarding, precipitation, than in the usual representation of output of climate models, which comes down to annual mean values of precipitation.

As impacts mostly apply to small geographical areas, the larger climate models are not well suited to produce the required data because they are not yet able to deliver reliable results on local scales. Especially the frequency and intensity of rain patterns are to a large extent locally determined. Insufficient resolution of the output of the larger models leads to precipitation changes which are not consistent when considered from a meteorological perspective. Basically, there are three known routes which can be taken to circumvent this resolution or 'downscaling' problem. 'Transfer functions' can be used to translate large-area averages into point estimates, the output of more complex climate models like GCMs can be used as input for smaller high-resolution limited-area models -like HIRLAM which is used by KNMI- to obtain information on smaller spatial scales, and stochastic models can be used to reproduce an instrumental record and, when succesful, to produce a record for a situation under CO2 doubling.

- The transfer technique or the transformation method is based on instrumental records. Hereby, it is assumed that established meteorological relationships, which are described mathematically, will hold, e.g. between atmospheric pressure, temperature and precipitation. This seems realistic as the interdependence of these relationships is determined by the laws of physics. As a next step, these relationships are used to transform the instrumental record to a new one under the assumption that, for example, the yearly mean temperature will have increased by two degrees Celsius. In reality this means that, for instance, daily precipitation amounts for the current situation are multiplied by a temperature dependent factor, which is derived from the mathematical description, to calculate future amounts of precipitation. Additional advantage of this technique is that it uses two independent sources of information, i.e. output of climate models, for the future change in temperature, and instrumental records to which this temperature change can be applied to obtain changes in other variables.
- The use of high-resolution models to process output of larger models is often called 'nesting' or deterministic downscaling. It can be considered as the most accountable route in a physical sense as the high-resolution models solve all fundamental equations describing physical processes on each time step. However, when using this technique the same disadvantages are encountered as when using the larger models: the method is time consuming and expensive.
- Stochastic modelling or downscaling uses statistical relationships, which are based on the characteristics of instrumental records, to reproduce the records of the past. When successful they are used to simulate records which apply to the future situation of enhanced CO2. In this respect stochastic simulation can be considered as the manipulation of a variable based on its statistical characteristics in the past to predict the probabilities of various possible outcomes for the situation in the future.

How to produce results which can be used by policymakers to convince the general public of the seriousness of the issue of global warming?

During the last several years it has become much more difficult to direct the attention of the general public towards the climatic effects of the anthropogenically enhanced greenhouse effect. This is seen by many as an undesirable situation. This loss of attention may be attributed to several independent processes or developments. Three important ones will be identified here.

A development of the last decade leading to fading interest is probably the relatively bad socio-economical situation, especially when the societal participation of people is considered. Because of this, many people do not have the luxury to interest themselves to the climatic-change issue which is after all a long-term issue. From the point of view of a climatologist there is no answer as to how to get these people involved in addressing global warming.

A process leading to a loss of attention, even among people who are interested, is the fact that scientific results presented on the matter often seem to contradict each other. From a scientific point of view there is nearly never a contradiction involved. On the other hand, the complexity of the climatic system, in combination with the fact that the characteristics of this system are often dealt with on significantly different temporal scales and the fact that the properties of the climatic system can be dealt with on different levels of abstraction, may lead to opposing statements. For instance, climate will cool -in about 50.000 years another ice age will be encountered- versus climate will warm -in about 50 years we will encounter temperatures higher than what we have experienced the last million years. Another example: the future climate is not predictable -the climatic system is a real-life chaotic system of which the behaviour is unpredictable by definition- versus the future climate is predictable -if we apply conditions, like for example that the climate models are telling us the truth in the sense that they correctly simulate one of many future realisations of the (future) climate, we may state that the climatic system has a (limited) predictability. The real problem, though, is the interpretation of these paradoxical statements by people who do not have fundamental knowledge about the climatic system. The best informed will be confused at best, while they most likely retain the idea that the climate will actually change. The least informed will -in the worst case- think that it may well be so that nothing will happen to the climate. There is no reason to believe that transferring knowledge and information to the general public will change this situation; the topic is just too complex and there are just too many seemingly contradicting stimuli offered by the media and else. Based on this it is here proposed to put more emphasis on the use of persons with authority within the climatological society or, in other words, to make more use of expert opinion. Experts should tell the public what is going on. Additional advantage of the use of expert opinion is the fact that accurate predictions will be avoided -human beings are not deterministically operating climate models- which will leave less ground for seemingly conflicting statements like, for example, that model A calculates that temperatures will have increased by 2 °C in 2050 and model B by 3 °C.

A third point which might explain why it is so hard to get the general public involved in the climate-change issue is the fact that many movements who have an interest in the occurrence of climatic changes, both negatively and positively, influence public opinion by spreading information which is either not relevant -but diverts the attention- or not accountable from a climatological point of view. In addition, this kind of information often contains value judgements like, for example, that the greenhouse effect is a serious threat or a hoax. For most people it is hard to decide whether this kind of information is sound or unsound, especially when it is provided by well-known scientists. Alternatively, these scientists make it often easier for an invididual to thrust its own feelings on the matter because they will always be strengthened by a specific expert. In this case also, it is proposed to put more emphasis on the opinion of experts in the field of climatology.

Modelled wisdom, added wisdom and added ignorance; discussion of the results of a case study.

In this study an attempt has been made to present future climatic change in a quantitative probabilistic way, based on a simple and transparent method. Taking the averaged temperature output from a sample of state-of-the-art coupled GCMs and the assumption that the differences in output comply with a normal distribution as basis, this output has been adapted to incorporate processes which are known to influence the climate but are not yet accounted for by the models. Incorporation of these processes resulted in all cases an increase of the probabilistic temperature range sometimes accompagnied by a correction of the most probable temperature change. In addition a correction has been made for ignorance about many processes which influence climate but which have not yet been elucidated and for ingnorance due the effects of smaller scale physical processes which are not (yet) resolved by the models. This method resulted in quantitative probabilistic outcomes for the climate on three geographical scales for the middle of next century.

The method shows that it is possible to produce quantitative probabilistic results in a way that is both accountable and simple. At the same time should it be recognized that the method relies heavily on the assumption of a normally distributed spread in the output of climate models. In addition, adaptation of the calculated most probable change in temperature including its associated probability distribution, has been based on the incorporation of many additional processes of which the quantification could be based on a few samples only: each adaptation was based on four values at most. And even then, these values were in almost all cases estimates -though these in turn are mostly based on physical models- which can hardly be validated because they concern a future state of the climate. In other words, the resulting probability distribution is largely based on quantifications of uncertain processes of which the importance has been subjectively assessed. So, whether the results of this approach can be used for scientific, policy or other purposes largely depends on the acceptance of the method in its present state by the user (as it is the case with all other methods as well).

We note that the method can very easily be adapted to incorporate new results or insights as well as that it can be based on any other statistical distribution, if required. This information may be of particular relevance for impact scientists who are often most interested in predicted changes in (the distribution of) extreme values. They should know that the changes in the extremes as presented in Chapter 6 -the probability of temperatures lower than -273.15 °C are also possible according to he results- are are an artefact of the calculation method used, more than a prediction based on physics or observations. This should not be a reason to dismiss these results. The question impact scientists should rather pose is whether there are reasons to assume that the calculated changes in extremes will not occur in reality, for instance because the use of a normal distribution does not comply with reality.

RECOMMENDATIONS

To obtain probabilistic climatological results with the smallest distribution possible:

General circulation models produce output which is best suited to statistical analysis on different levels of accuracy.

A simple and at the same time comprehensive analysis based on GCM output has been presented in Chapter 6. An important point that has been dismissed in this analysis is that the calculations leading to the probabilistic statement have been based on the assumption that the model results are distributed Gaussian. If we consider, among other things, past climates there is more reason to assume a non-Gaussian distribution, though there is no reason to opt for any specific non-Gaussian distribution at present.

A more fundamental approach is as follows. It is known from both modelling studies as well as theoretical exercises that the climatic system is sensitive to small perturbations. Thence, it can be stated that basic knowledge with respect to the probability of the occurrence of a distinct climatic state can only be gained by performing Monte-Carlo simulations or sensitivity studies with stochastic elements.

To obtain probabilistic climatological results suited for impact studies:

Two constraints are imposed. The first one is that a method should be found which can be used at present. The best results will probably obtained when using the results from the method proposed above, i.e. probabilistic statements based on Monte-Carlo simulations or sensitivity studies, as input for smaller-scale models of higher resolution. However, these kinds of results are not yet available to the extent required; because of the computer time involved this situation will probably remain for the next several years. Thus, use of output of runs yet performed with coupled GCMs is suggested.

The desires of impact scientists are the other constraint. Depending on the process they investigate they are interested in specific changes in statistical characteristics of one or more climatic variables. The process of interest may be changing maxima in spring tide, but also changes in the rate of desertification. This determines largely which kind of model should be used to translate the output of the larger-scale models into the desired kind of information on smaller scales; i.e. a 'nested' higher-resolution model, a transformation model or a stochastic model. Not all three models are equally suited for all problems.

Accounting for both constraints, the proposed method to come to probabilistic statements on climatic change for impact studies is as follows. The quality of the output of the different coupled models should, with regard to specific climatological variables of interest as defined by impact scientists, be rated by experts in order to obtain a hierarchy of reliability. Then the preferred smaller-scale model should be used to simulate the climatological information needed from the output of, preferably, all coupled models. The associated probabilities should be attributed in accordance with the hierarchy as established by expert opinion. Quantitative information about the temporal evolution of the variables of interest, which may put the results for a well-specified period in the future in perspective, may be obtained by using the (weighed) output for different decades of the models considered.

To obtain probabilistic climatological results which are most suitable to inform the general public about climatic change:

The strategy should be to avoid overly accurate results on the one hand, thus avoiding confusing paradoxes, and to use authority on the other hand. Both actions will likely stress the agreement that exists currently in the scientific community and they may thus give reason to put confidence in the predictions.

Both actions are combined when expert opinion is used. Experts do in general not present overly precise estimates when talking in public and because they are experts they will have authority. The use of expert opinion will most likely not address the problem of how to get people involved who have more direct and short-term problems to deal with. However, the use of expert opinion may influence people who are in some way interested in the phenomenon. It can be imagined that the more direct the communication between experts and (groups of) individuals, the stronger the effect. Considering this it is here proposed to bring experts as close as possible to the general public; an idea which has also been brought forward during the project 'Policy Options Addressing the Greenhouse Effect' of Klabbers et al. (undated). To provide the audience with probabilistic statements it is proposed that the experts should be encouraged to present climatic information in the form of estimates or preferably, due to assumed better communication, in the form of bets.

When probabilistic information should be provided to the general public in a less direct sense, i.e. via the written press, it may turn out to be advantageous to use the results of a survey of expert opinion. The media often ask persons with adverse -and in many cases wrong- ideas to express their meaning, because that is considered as news; repeating well established ideas, for instance the IPCC consensus, is not. The point is that the general public is not able to discriminate between the opinions of a specialists or a non-specialist. Indeed, they are often both presented as specialists and opposing ideas often seem to get more attention than views in line with scientific consensus. So, in many cases the public is left with the unjust feeling that science does not know yet. A survey of expert opinion may address this problem effectively because it can incorporate opposing ideas. Because a well controlled survey includes a ranking of all experts -they should qualify themselves and the other participants on various fields of interest- opposing persons will rank much lower -if their ideas are considered scientifically unsound, that is. This means that their opinion will be given less weight and, thus, that they will influence the commonly held views to a smaller extent than usual via the media.

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ACKNOWLEDGEMENTS

The evolutionary process which lead to the final form of this report has been given guidance by a commission of scientists which acted as a sounding board. This commission consisted of the following persons:

Dr Ir W. Biesiot of the Center for Energy and Environmental Studies IVEM of the University of Groningen RUG,
Dr L. Janssen of the National Institute of Public Health and Environmental Protection RIVM,
Dr L.A. Meyer of the Directorate Air & Energy of the Directorate-General for Environmental Protection of the Dutch Ministry of Housing Spatial Planning and the Environment VROM,
Dr J.D. Opsteegh, head of the section of Predictability Studies of the Royal Netherlands Meteorological Instititute KNMI,
Dr A. P. van Ulden, head of the section of Atmospheric Research of the Royal Netherlands Meteorological Instititute KNMI,
Dr A. van Wijk of the department of Science Technology and Society N&S of the University of Utrecht UU.

All members of the commission are gratefully acknowledged for their comments on earlier drafts of this report and for initiating fruitful discussions during the meetings. This equally applies to Dr R.J. Haarsma of the section of Predictability studies of KNMI and Dr M.S. Krol of the Global Change Department of RIVM.

Special gratitude goes to the leader of the project 'Probabilities of Climatic Change', Dr G.P Können, head of the working group on Climate Scenarios of the Royal Netherlands Meteorological Instititute KNMI, for giving well-dosed amounts of stimuli at the right moments.

A last remark is directed to all people who commented on the study, but to Aad van Ulden in particular. Most remarks on earlier drafts concerned technical issues; they could in general be addressed quite simply. Some remarks were not always understood well directly after hearing. Just these remarks were afterwards considered the most valuable by the authors of this report, because they often provided new insights. However, new insights cannot be incorporated that easily in a study that both has to be finished in a relatively short amount of time -that is, six months in the case of the underlying study- and is already determined with respect to form and contents -that is, by the contents of the contract in the case of the underlying study. Alternatively, it is considered as regrettable by the authors that this report could not provide the opportunity to find response to some of the new and deeper insights obtained during the discussions with some of the members of the commission.

APPENDIX I

Request for information sent to scientists working at KNMI

S.V.P. binnen kamer laten circuleren

De Bilt, 080994

L.S.,

Momenteel ben ik bezig met een inventarisatie van (reeds uitgevoerd) binnen- en buitenlands klimaatonderzoek dat tot doel heeft de toekomstige verandering van het klimaat in termen van waarschijnlijkheden uit te drukken. Op dit gebied is nog weinig onderzoek verricht. Dit is te verantwoorden door te wijzen op de complexiteit van het klimaatsysteem en, dus, van klimaatmodellen. Dit gegeven, de complexiteit van het klimaatsysteem en klimaatmodellen, zou echter juist ook een tegengestelde ontwikkeling kunnen verantwoorden. Immers, wat is de waarde van een uitkomst van een model dat een complex systeem beschrijft zonder dat daar een uitspraak over de waarschijnlijkheid bijgeleverd wordt!?

Mijn vraag aan u is nu of u mij bij deze inventarisatie zou willen helpen. Dit kan door mij ofwel op de hoogte te stellen van lopend of reeds uitgevoerd onderzoek in binnen- en buitenland binnen genoemde doelstelling, of door mij in te lichten over (op stapel staande) publicaties over dit onderwerp. Ik ben tevreden met elke studie waar een kansuitspraak met betrekking tot de verwachte klimaatverandering gedaan wordt of waar hier vanuit een fundamenteel-theoretische invalshoek op ingegaan wordt. Drie voorbeelden:
1) Het Hadley Centre heeft de standaarddeviatie uitgerekend van de door zes modellen in zeven 2xCO_2-runs berekende temperatuurverandering. Door een normaalverdeling te veronderstellen kon het 10 en 90% betrouwbaarheidsinterval berekend worden van de uitkomsten (ongedateerd document door Viner en Hulme, Contract Reference Number PECD 7/12/96)
2) Gruza en Rankova (Soviet Meteorology and Hydrology, No. 4, 1991) hebben gekeken hoe vaak er de afgelopen 100 jaar een relatieve CO_2-stijging heeft plaatsgevonden die vergelijkbaar in grootte is met de voor de komende 10, 15 en 20 jaar voorspelde relatieve stijging. Vervolgens werd gekeken hoe groot de temperatuurverandering in de gevonden periodes geweest is. Via een statistische analyse werd vervolgens de te verwachten temperatuursverandering berekend voor de drie genoemde periodes, inclusief het 25-75% betrouwbaarheidsinterval.
3) Tennekes, zich baserend op Karl Popper, in Weather 47, 343 [1992]): "....a prediction that does not include a calculation of its predictive skill is not a legitimate scientific product." en ".....if we wish to make a deterministic forecast, it will not do to make anything less than a deterministic skill forecast. Don't retreat into statistics when the going gets tough,....."..

Bij voorbaat dank voor de genomen moeite,

Wieger Fransen,

kamer A 177, tel. 675

APPENDIX II

Request for information sent to scientists working within the Dutch National Research Programme on Air Pollution and Climate Change NRP

De Bilt, 150994

L.S.,

Momenteel ben ik, in opdracht van het Ministerie van VROM, bezig met het project 'Waarschijnlijkheid klimaatverandering'. Het eerst af te ronden onderdeel van het project is de inventarisatie van (reeds uitgevoerd) binnen- en buitenlands klimaatonderzoek dat tot doel heeft de toekomstige verandering van het klimaat in termen van waarschijnlijkheden uit te drukken. Op dit gebied is nog weinig onderzoek verricht. Dit is te verantwoorden door te wijzen op de complexiteit van het klimaatsysteem en, dus, van klimaatmodellen. Dit gegeven, de complexiteit van het klimaatsysteem en klimaatmodellen, zou echter juist ook een tegengestelde ontwikkeling kunnen verantwoorden. Immers, wat is de waarde van een uitkomst van een model dat een complex systeem beschrijft zonder dat daar een uitspraak over de waarschijnlijkheid bijgeleverd wordt!? Over de betrouwbaarheid van de modeluitkomsten heb ik het dan overigens nog niet eens (zie hiervoor onder andere Tennekes in Weather 47, 343 [1992]).

Mijn vraag aan u is nu of u mij bij deze inventarisatie zou willen helpen. Dit kan door mij ofwel op de hoogte te stellen van lopend of reeds uitgevoerd onderzoek in binnen- en buitenland binnen genoemde doelstelling, of door mij in te lichten over (op stapel staande) publicaties over dit onderwerp. Ik ben tevreden met elke studie waar een kansuitspraak met betrekking tot de verwachte klimaatverandering gedaan wordt.
Drie voorbeelden:
1) Het Hadley Centre heeft de standaarddeviatie uitgerekend van de door zes modellen in zeven 2xCO_2-runs berekende temperatuurverandering. Door een normaalverdeling te veronderstellen kon het 10 en 90% betrouwbaarheidsinterval berekend worden van de uitkomsten (ongedateerd document door Viner en Hulme, Contract Reference Number PECD 7/12/96);

2) Gruza en Rankova (Soviet Meteorology and Hydrology, No. 4, 1991) hebben gekeken hoe vaak er de afgelopen 100 jaar een relatieve CO_2-stijging heeft plaatsgevonden die vergelijkbaar in grootte is met de voor de komende 10, 15 en 20 jaar voorspelde relatieve stijging. Vervolgens werd gekeken hoe groot de temperatuurverandering in de gevonden periodes geweest is. Via een statistische analyse werd vervolgens de te verwachten temperatuursverandering berekend voor de drie genoemde periodes, inclusief het 25-75% betrouwbaarheids-interval;

3) Op basis van een Delphi onder 21 klimaatexperts werd in 1978 de uitspraak gedaan dat de kans dat het tussen de 0.6 en 1.8 °C warmer wordt tussen 0-80 °N in 2000 ten opzichte van het gemiddelde in de periode '65-'69 0.1 is. De kansen dat het tussen de 0.25 en 0.6 °C warmer wordt, dat het tussen de 0.25 °C warmer en 0.05 °C kouder wordt, dat het tussen de 0.05 en 0.3 °C kouder wordt en dat het tussen de 0.3 en 1.2 °C kouder wordt, werden in hetzelfde onderzoek berekend als zijnde respectievelijk 0.25, 0.30, 0.25 en 0.10 (Climate Change to the Year 2000. National Defence University, Washington D.C., 1978).

Ook zou u mij zeer verplichten door mij, als u zelf onderzoek op dit gebied uitvoert of als u hier vanuit een fundamenteel-theoretische invalshoek zeer eigen ideeën op nahoudt, hierover in te lichten.

Bij voorbaat dank voor de genomen moeite,

Wieger Fransen,
Wetenschappelijk medewerker KNMI

doorkiesnr	030206675
faxnr	030210407
e-mail	fransen@knmi.nl

APPENDIX III

Request for information sent to scientists working on projects aimed at providing quantitative probabilistic statements on climatic change

De Bilt, 1994

Dear

I have been informed by
that you are currently undertaking studies on the probability of a change in the climate in a quantitative sense, i.e. results in terms of confidence limits, hypothesis rejection at well defined levels of confidence, probabilities, bandwidths, et cetera.
My current task at KNMI is just to answer the question whether it is possible to present time-dependent climatic change predictions, with respect to larger as well as to smaller geographical scales, which are based on probabilities. This as opposed to a presentation based on uncertainty, as is the common method. The study is commissioned by the Ministry of Environment of the Netherlands whose long-term objective it is to base climate policy on risk-analysis. For this, quantitative, stochastic statements about the predicted climatic change are needed. It has been my wish to start this project with an inventory of present and on-going research on this topic. For this I need your cooperation.
I would like to ask you, if you can identify more research groups, or scientists for that matter, than are listed in the accompanying table and who are or have been studying, c.q. publishing on the above-mentioned topic. These groups may have come to probabilistic statements by using methods like, for instance, time series modelling, palaeo-analogue modelling, and expert-opinion surveys.

I Thank you in advance for your efforts,

yours sincerely,

Wieger Fransen

scientist

Wieger Fransen
KNMI
P.O. Box 201
3730 AE DE BILT
The Netherlands;
e-mail: fransen@knmi.nl

APPENDIX IV

Announcement for a discussion sent to scientists working at KNMI on the modelling of the hydrological cycle

Aan: Anton Beljaars, Rob van Dorland, Bert Holtslag,
Erik van Meijgaard, Pier Siebesma, en Aad van Ulden

Discussie, dinsdag 31 januari, 15.00 uur, B7

De gevoeligheden van gekoppelde klimaatmodellen voor veranderingen in de manier waarop de hydrologische kringloop gemodelleerd is.

Achtergrond:
In opdracht van VROM werken Alice Reuvekamp en ik aan het project 'Waarschijnlijkheid klimaatverandering'. Doel van het project is te komen tot kwantitatieve probabilistische uitspraken met betrekking tot de verwachte temperatuurverandering voor een zeker tijdstip in de toekomst voor de wereld als geheel en voor Noord-West Europa (Nederland). Hiertoe worden in eerste instantie resultaten van simulaties met vier gekoppelde klimaatmodellen gebruikt (**conventional wisdom**). Door de uitkomsten van deze simulaties te middelen en een normaalverdeling te veronderstellen worden de gewenste kansuitspraken verkregen. Om te corrigeren voor modelonvolkomenheden worden ook schattingen gemaakt voor zaken als 'gevoeligheid voor de begincondities' en 'aerosolen' (**added wisdom**). Ook wordt onder het kopje 'added wisdom' ingegaan op scenario's die wel als plausibel kunnen worden aangemerkt, maar die niet door modellen worden gerepresenteerd. Hierbij moet men denken aan het omleggen van circulatiepatronen in de oceaan en de mogelijkheid dat klimaatverandering zich uit in extra bewolking en niet zozeer in temperatuursverhoging. Verder wordt nog een willekeurige mate van onzekerheid toegevoegd die toe te wijzen is aan het feit dat we er zeker van zijn dat we processen vergeten zijn (**added ignorance**).

De vraag:
Zaken die tot nu toe meegenomen zijn onder de kopjes 'conventional wisdom' en 'added wisdom' zijn bijna alle gebaseerd op modeluitkomsten. Het baseren van onzekerheden op slechts modeluitkomsten houdt een zeker risico in omdat zó veel gevoeligheden van de modellen voor veranderingen in processen die deel uitmaken van het klimaatsysteem -met name de grootste gevoeligheden?- mogelijk onder tafel blijven. Zo heb ik begrepen dat een gekoppeld model zonder flux-correctie al snel onrealistische waarden berekend voor bepaalde parameters. Als gevolg hiervan gaat het door de modellen berekende huidige klimaat zelfs zonder verstoring veranderen ('drift'). Uit informatie die inzicht geeft in het hoe en waarom van deze 'drift' is wellicht enige grond te halen om de meest waarschijnlijke waarde voor de verwachte temperatuurverandering aan te passen en de standaarddeviatie te veranderen. In dit licht leek het mij verstandig om twee discussieronde's op het KNMI te organiseren. Graag zou ik enig kwantitatief inzicht verkrijgen omtrent twee processen die, voor zover ik begrepen heb, de huidige klimaatvoorspellingen erg onbetrouwbaar maken. Dit zijn modellering van de hydrologische kringloop en van de oceaancirculatie.

Doel van de discussierondes:
Doel van de discussieronde's is enerzijds te komen tot inzicht met betrekking tot de onzekerheden van modeluitspraken in een kwalitatieve zin. Anderzijds zal worden getracht tot kwantitatieve uitspraken te komen met betrekking tot deze onzekerheden.

1) "Wat is de bandbreedte die ik moet toevoegen aan de door mij reeds gedane uitkomsten?",
2) "Zijn er scenario's denkbaar die structureel afwijken van, bijvoorbeeld, de IPCC voorspellingen?", en
3) "Wat is de aanpassing die ik ten aanzien van de door ons berekende meest waarschijnlijke temperatuurverandering moet doorvoeren naar aanleiding van de discussie",

zijn drie vragen waarop ik een antwoord zou willen krijgen tijdens genoemde discussierondes.

Uitspraken van deelnemers aan de discussieronde zouden gebaseerd kunnen worden op:
- Eigen ervaringen met modelaanpassingen:

Wat kunnen de gevolgen zijn van de implementatie van een nieuw fysicapakket? Wat kan er gebeuren als parameterisaties worden aangepast? Wat kan er misgaan bij het verhogen van de resolutie? Hoe snel gaat een gekoppeld model 'drift' vertonen als afgezien wordt van flux-correctie? Wanneer kan, in het licht van de mogelijkheid dat klimaatregime's bestaan, worden gesteld dat een modeluitkomst niet (meer) realistisch is? Wat kan men leren uit het gegeven dat een aantoonbaar beter fysicapakket, voor bijvoorbeeld convectie, bij implementatie in een groter model zorgt voor slechtere modeluitkomsten? Is er sprake van inteelt bij de modellenbouwers waardoor de modellen veranderingen aangeven die weliswaar in alle dezelfde richting wijzen maar desondanks alle in de verkeerde richting wijzen? Hoe gaat het tunen van een model in zijn werk en wat zijn de nadelen van dit tunen?

- Andermans ervaringen met modelaanpassingen:

Is er gepubliceerd over 'niet-publiceerbare uitkomsten' van modelsimulaties? Zijn er anecdotes te verhalen die ertoe bij kunnen dragen dat het conceptuele begrip bij leken omtrent mogelijkheden en onmogelijkheden van klimaatmodellering toeneemt? Wat kunnen we leren van het feit dat een aanpassing van het stralingsschema in het ... model ervoor zorgde dat de netto uitstraling aan de top van de atmosfeer met 5 watt per vierkante meter toenam? En van het gegeven dat aanpassing van het ... schema in het Hamburgmodel ervoor zorgde dat de verdeling van neerslag over het jaar voor een bepaald aantal plaatsen die als referentie dienden eerder minder leek op de werkelijkheid dan meer?

Methode:
De twee discussieronde's zullen ingeleid worden door een ter zake kundige (vervalt i.v.m. tijdgebrek organisatie). Mogelijk zal de inleiding worden afgesloten met stellingen die tot doel hebben de discussie open te breken.
Tijdens de discussie zal de nadruk komen te liggen op het vaststellen van wat de extremen in opvattingen zijn. Er zal niet getracht worden tot een consensus te komen.
Aan de hand van de verkondigde meningen zal getracht worden tot een kwantitatieve schatting te komen van zowel de toe te voegen bandbreedte als de aanpassing van de meest waarschijnlijke temperatuurverandering op het moment van twee keer CO_2. Enige moeite zal gedaan worden opdat iedereen zich in de voorgestelde aanpassing van de temperatuurprognose kan vinden.

Wieger Fransen
310195

APPENDIX V

Comments on an earlier draft provided by peer-reviewers

To : Wieger Fransen
Organization : KNMI
Facsimile no. : 030 - 210407

From :
Telephone : (31)
Facsimile no. : (31)
Date : 7 april 1995
Subject : rapport waarschijnlijkheid klimaatverandering

Beste Wieger,

Hier enkele commentaren op het rapport. Ik heb alleen gekeken naar H 5, en de discussie/conclusies erover in H 6. Het soort resultaten, daar besproken, lijkt me heel bruikbaar. Ik mis echter nog twee dingen: 1) een discussie over de interpretatie van de gegevens en 2) wat is nu de haalbaarheid van de methode, in bredere zin.

Ad 1). Veel van de spreidingen worden geschat uit gegevens uit slechts weinig bronnen (4 GCMs, 4 sulfaat-koelings schattingen, ...). Uit weinig samples kan men geen verdeling schatten; een hypothese over de verdelings-functie is niet te falsificeren met zo weinig gegevens. Bovendien wordt, zeker op de zonale/regionale schaal de uiteindelijke variantie vooral bepaald door de bijgeschatte sigma's. De gepresenteerde 2-percentielen (fig 19,20) en 95% betrouwbaarheids-schattingen worden volgens mij dan ook nauwelijks door de data ondersteund, en zouden zeker kritisch bediscussieerd moeten worden. Dit is extra van belang omdat de impacts vooral bij grotere afwijkingen van het gemiddelde zullen optreden. Er zijn ook tussenwegen, zoals het geven van een of twee hogere momenten van de verdeling en de verantwoordelijkheid over de te kiezen verdeling aan de gebruiker overlaten. De uitspraak 'de kans is 16% dat het over 60 jaar minstens 5.4°C warmer is in Nederland' zou wel eens veel geciteerd kunnen gaan worden, en handvaten voor de interpretatie van/onzekerheid in de uitspraak zijn niet voorhanden.

Enkele kleine puntjes: is de kans om binnen een standaard deviatie van het gemiddelde te liggen 66 of 68% (blz 64 ev.); in de verdelings-plaatjes staat vertikaal de kansdichtheid uitgezet, niet de kans.

Ad 2). Naar ik begrepen heb, is het praktische deel van de studie deels als haalbaarheids-studie bedoeld. De haalbaarheid wordt echter niet besproken. Waarom zijn de 2.5 en 97.5 percentielen van de verdeling verdedigbaar (en niet alleen mu, sigma), welke gegevens hebben daartoe bijgedragen. Dit zou duidelijk maken of de methode, met de beschikbare gegevens, ook toepasbaar is op bv. regenval, maandelijkse temperaturen etc., of welk deel van de resultaten naar verwachting door de methode aan te leveren zijn.

Succes met het afronden van het rapport,

cc.

Bestemd voor : Wieger Franssen
Afkomstig van :
Afdeling :
Datum : 10 april 1995
Onderwerp : Waarschijnlijkheid Klimaatverandering

Telefoon :
Telefax :
e-mail :

Eerste pagina van 2 pagina's

Beste Wieger,

1. Veel robuster verhaal geworden en ik heb veel waardering voor je creativiteit om een dergelijke methode op te zetten en te quantificeren.

2. Gezien de "nieuwheid" van de methode en het daarmee samenhangende gebrek aan harde en samenhangende gegevens is het wellicht beter om de haalbaarheid van de methode te evalueren dan tamelijk deterministische uitspraken te geven in de figuren 19 en 20. Dit is zeker illustratief maar maar zeker niet zeker.

3. M.b.t. de methode:

- m.b.t. het klimaat systeem schrijf je: "The probabilities when added do not necessarily lead to a 100% coverage of all probabilities" (pag 5). Dit begrijp ik niet goed en doe je daar nog wat mee in het vervolg?
- Op pag 8 in de box: "The statistical representation of a climate variable will not have the same characterisics etc" , Hoe werkt dat door in de methode?
- is het systeem transituve of intransitive (optreden van ijstijden, pag 22, 23 en 35 is nog lastig).
- opmerking van Lorentz; the "noodzaak" dat climate models "stochastisch zijn".

Dit is mijn inziens hier relevant omdat de veronderstelde antropogene verstoring (T-verandering) tamelijk groot is.

- the system should be well defined (pag 25)
- tot nu toe geen probabilistic statements based on direct output from coupled GCM's (pag 35); dat doe je nu wel, kan dat?
- terugkoppelingen in het systeem zijn vermoedelijk het belangrijkst voor de uiteindelijke uitkomst (het gemiddelde) en zijn niet in een spreiding (of kansuitspraak) te verwerken, daarvoor is proceskennis nodig.

4. De kwantitatieve uitwerking:

- de studies van Viner and Hulme en Woo zijn interessant maar de resultaten (te) kort besproken. Kan de studie van Woo niet gebruikt worden om de sigma van temperature variability bij 2xCO2 te schatten?
- je weegt de resultaten van de 4 GCM's hetzelfde voor het berekenen van het gemiddelde en de sigma. Kan dat gezien de verschillende uitgangspunten (tabel 2 op pag.68)
- weging van radiative effects van aerosols ook hetzelfde genomen en extremen bepalen dan het gemiddelde. M.i. is juist het regionale effect van aerosolen groot en overal -0.4 is m.i. niet juist; indirect effect is nog niet gekwantificeerd (IPCC)
- er is maar een zonale waarde (GFDL) in tabel 3 (pag 71) maar je neemt wel een verdeling aan (fig 18) etc
- zoals je zelf al aangeeft zijn emissiescenario's van groot belang bij gekoppelde dynamische modellen. Dit geeft eerder een systematisch effect dan een vergroting van sigma.
- figuur 18; geldt op bepaald tijdstip, bij 2x CO2, bij bepaald emissiescenario, en nog een aantal aannames, zie bovenstaande en

is gebaseerd op een "dynamische" verdeling af op basis van resultaten van dynamische (gekoppelde) modellen. Mijns inziens heeft die verdeling dus ook een "moment-karakter" waarvan het de vraag is of die gaussisch is en of daar niet een additionele spreiding bijzit. (niet lineaire relatie tussen parameters)

- dT zonaal en dT regionaal kunnen niet overal hoger zijn dan dT globaal; ergens moet het kouder zijn om op het gemiddelde uit te komen; het is een symetrische verdeling, het kan dus in Nederland kouder worden dan het gemiddelde.
- figuur 19 en 20 zijn gebaseerd op een "rechteroverschrijding" van figuur 18.

De kans is even groot dat er geen temperatuurstijging optreedt, "linkeroverschrijding". T.a.v. van risico is natuurlijk alleen de rechteroverschrijding van belang.

- de linearisering in figuur 19 en 20 is zeker een vereenvoudiging,verantwoord?

5.Kortom: ook IPCC doet uitspraken over toekomstige temperatuur veranderingen en geeft een range; je moet m.i. wel een "harde en betrouwbare" verdeling kunnen vaststellen wil je een verdergaande relevante uitspraak kunnen doen. Daar ben ik op basis van huidige kennis en bovenstaande nog voorzichtig mee of we dit nu kunnen.

Met vriendelijke groet,

c.c.

Eerste pagina van 1 pagina

Beste Wieger,

Tijdens mijn bezoek aan het KNMI had ik je nog het volgende willen toevoegen m.b.t. je rapport over "Waarschijnlijkheid klimaatveradering". Toen niet, nu wel:

- in de aanloop van het project heb ik je gesuggereerd dat ook antropogene ontwikkelingen, dus scenario's sterk het tijdverloop van klimaatverandering kunnen bepalen. De snelheid van klimaatverandering hangt niet alleen af van de karakteristieken van het klimaatsysteem.
- De figuren 18 en 19 hangen dus sterk af van het scenario dat je kiest en je zou dat zeker moeten aangeven en in de bespreking van waarschijnlijkheden (is het niet een Poissonverdeling) dat de temperatuur "after 60 years" meer dan x C zal stijgen/dalen meenemen. Ook de maatschappelijke ontwikkelingen zelf zijn een bron van onzekerheid.

Met vriendelijke groet,

---

13 april 1995

Aan: Wieger Fransen, KNMI

Beste Wieger,

Hierbij gaat mijn commentaar op je risico-klimaat-studie, die ik met veel genoegen en waardering heb gelezen. Aangezien ik een en ander thuis werkend heb gezien en opgeschreven, ontbreken de standaard brief kenmerken - mijn oude printer kan niet beter dan dit.

De opbouw van het betoog acht ik in orde. Per hoofdstuk heb ik het volgende commentaar:

1: We hebben hier te maken met een eigenaardige vorm van risico, nl een continue (en toenemende) lozing van broeikasgassen met een mogelijk (probabilistisch te beschrijven) drempel-effect op klimaatgerelateerde parameters naast wellicht een min of meer causaal verband met bepaalde parameters (denk aan biomassa groeiparameters etc); en de gevolgen zijn deels positief deels negatief van aard. Dit lijkt niet erg op anders voorbeelden van bestudeerde risico's (een kerncentrale die kan lozen, industriële installaties met plof-kansen, chronische emissie van stapelende stoffen die pas na een drempeldosis effecten veroorzaken, risico-beoordelingen in de eco-toxicologie). Misschien nog het meest op de laatste twee categorieën (in het bijzonder die in de eco-toxicologie, want die zitten ook steeds met achtergrondbelasting en de fragiliteit van de te beschermen systemen), maar ook daarvoor geldt dat de kwantitatieve risico-analyse ervan nog in de kinderschoenen staat. Het begrip risico is "in jouw geval" niet eenvoudig te definiëren - zoals vergelijking met Vlek1990 je ongetwijfeld heeft geleerd. Essentiële kenmerken zijn dan (subjectieve inschattingen van) de distributie van voor/nadelen over groepen (plus de invloed van de samenhang tussen die groepen in tijd en ruimte - denk aan internationale ruzies, intergenerationele kanten), en (subjectieve inschattingen van) de beheersbaarheid van de oorzaken en de gevolgen.

De belangrijkste les (voor mij) uit de risico-discussies is de noodzaak om eerst vast te stellen voor welk doel/besluit men deze techniek wil gaan gebruiken. Het heeft geen zin om een full-swing nucleaire PSA te gaan maken (die na stadium III resulteert in grote onzekerheidsmarges) als het om toetsing aan maatschappelijk aanvaardbare risico's gaat; wel om het doel is het vergelijken van ontwerpen of technische ingrepen.

Dus, hoe ziet het vraagstuk er hier uit, en dat is mijn commentaar bij H1 - een duidelijker plaatsbepaling van je eigen studie is nodig - en dat vergt volgens mij de volgende opbouw in H1:

* "klimaat" bestaat niet
* "verandering ervan" is continu, en dus gaat het om het (normatief!) vaststellen van acceptabele delta's
* het is een typisch risico (zie boven)
* de distributie- en beheersbaarheidskwesties vragen om een inschatting, en daarbij speelt de klimatologie een rol
* en dan volgt de plaatsbepaling van je eigen studie

Wellicht is het nog een idee om nog even leentjebuur te spelen bij de ecotoxicologen (eisackers van het rivm is bv een goede) voor het resultaat van hun worstelpartij met de complexiteit van het probleem.

H2: De opzet van dit hoofdstuk past ook beter na een revisie van H1 in bovenbedoelde zin.
Wat mij betreft maak je ook een duidelijker onderscheid tussen concepten en recepten (voor de politiek) die nu nog wat door elkaar lopen. Wat mij betreft behandel je de complexiteit van het vraagstuk in H1 en laat dat verder buiten beschouwing in H2 (anders dan waar nodig bij de bespreking van essentiële concepten).

H3: Het slot van H3 gaat in de expertmeningen. Ik zou daar melding maken van onderzoek zoals van Roger Cooke en ook Jelle van Lenthe (is vorig jaar gepromoveerd op elicitatie van expertmeningen) om aan te geven dat dit meer is dan lukraak ondervragen van wat kennissen uit de buurt.

H4: OK

H5: OK - volgens mij moet je een duidelijker onderscheid maken tussen review en eigen werk. Dat lijkt me eenvoudig, maar wel erg verhelderend. Ook wat regels wijden aan nog andere mogelijkheden van combinaties en assessment van reeds bestaande resultaten en benaderingen.

H6: Het deel over je conclusies is nog niet uitgewerkt. Met name mis ik een duidelijk verhaal waarin de antwoorden op de oorspronkelijke vraagstellingen worden gegeven en gerelativeerd + een opzet voor vervolgonderzoek (voor jou en/of voor de onderzoeksgemeenschap) die dan wel de essentiële kennislacunes moeten gaan dichten danwel een discussie over waarom dat niet kan en in welke mate misschien etc.

Algemeen: Ik hou er niet van als een paragraaf eindigt met een beschrijving van wat in de volgende aan de orde zal komen. De inhoudsopgave is helder genoeg, en het gebruik van de boxen is zeer verhelderend en to-the-point.

Sterkte met de afronding,
met vriendelijke groet (ook aan Gunther!),

10aug95

Van:

Aan: Wieger Fransen

In mijn kommentaar over jou rapport zal ik mij beperken tot paragraaf 2.3. Je geeft een goed overzicht van het gedachtengoed van Lorenz en latere onderzoekers met betrekking tot het chaotisch gedrag van de atmosfeer. Mijn grootste bezwaar is dat je de indrukt wekt dat voorpselbaarheid van de atmosfeer het zelfde is als voorspelbaarheid van het klimaat. Op tijdschalen van decades is de dynamica van de oceaan van wezenlijk belang voor de evolutie van het klimaat (50% van het poolwaards warmte transport wordt verzorgt door de oceaan). De voorspelbaarheid van het gekoppelde systeem is afhankelijk van de tijdschaal en de plaats op aarde. Zo is het verloop van ENSO redelijk voorspelbaar als die eenmaal is ingezet. Een mogelijk ander verschijnsel met een langere voorpselbaarheids horizon zijn decadale fluctuaties in de thermohaline circulatie. Mijn advies is om hier wat meer aandacht aan te schenken.

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