Introduction

Purpose of the Report

The purpose of this report is to provide a scientific assessment of:

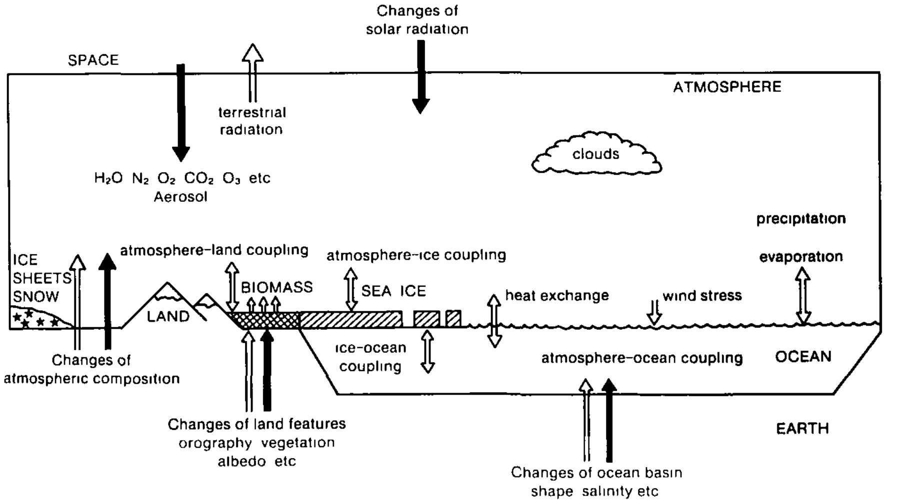
1. the factors which may affect climate change during the next century, especially those which are due to human activity;
2. the responses of the atmosphere-ocean-land-ice system to those factors;
3. the current ability to model global and regional climate changes and their predictability;
4. the past climate record and presently observed climate anomalies.

On the basis of this assessment, the report presents current knowledge regarding predictions of climate change (including sea-level rise and the effect on ecosystems) over the next century, the timing of changes together with an assessment of the uncertainties associated with these predictions.

This introduction provides some of the basic scientific ideas concerned with climate change, and gives an outline of the structure of the report.

The Climate System

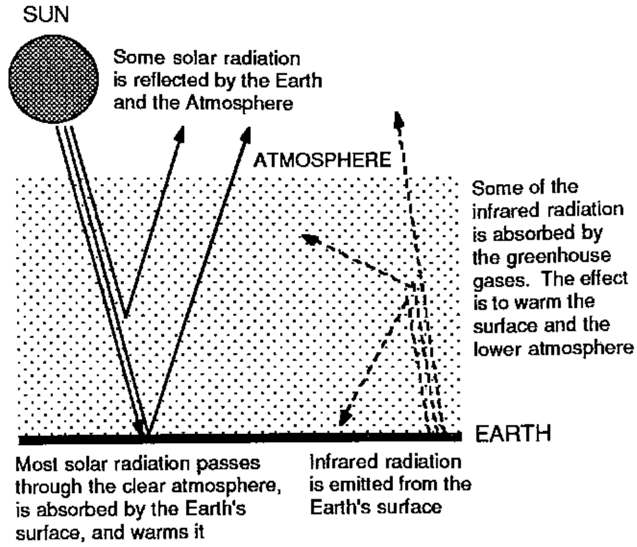
A simple definition of climate is the average weather. A description of the climate over a period (which may typically be from a few years to a few centuries) involves the averages of appropriate components of the weather over that period, together with the statistical variations of those components.



Schematic illustration of the climate system components and interactions. (from Houghton, J.T. (ed), 1984: The Global Climate; Cambridge University Press, Cambridge, UK, 233pp)

Fluctuations of climate occur on many scales as a result of natural processes; this is often referred to as natural **climate variability**. The **climate change** which we are addressing in this report is that which may occur over the next century as a result of human activities. More complete definitions of these terms can be found in WMO (1979) and WMO (1984).

The climate variables which are commonly used are concerned mainly with the atmosphere. But, in considering the climate system we cannot look at the atmosphere alone. Processes in the atmosphere are strongly coupled to the land surface, to the oceans and to those parts of the Earth covered with ice (known as the cryosphere). There is also strong coupling to the biosphere (the vegetation and other living systems on the land and in the ocean). These five components (atmosphere, land, ocean, ice and biosphere) together form the **climate system.**



A simplified diagram illustrating the greenhouse effect

Forcing of the Climate System

The driving force for weather and climate is energy from the Sun. The atmosphere and surface of the Earth intercept solar radiation (in the short-wave, including visible, part of the spectrum); about a third of it is reflected, the rest is absorbed. The energy absorbed from solar radiation must be balanced by outgoing radiation from the Earth (terrestrial radiation); this is in the form of long-wave invisible infra-red energy. As the amount of outgoing terrestrial radiation is determined by the temperature of the Earth, this temperature will adjust until there is a balance between incoming and outgoing radiation.

There are several important factors (known as **climate forcing agents**) which can change the balance between the energy (in the form of solar radiation) absorbed by the Earth and that emitted by it in the form of long-wave infra-red radiation - the radiative forcing on climate. The most obvious of these is a change in the amount or seasonal distribution of **solar radiation** which reaches the Earth (orbital changes were probably responsible for initiating the ice ages). Any change in the albedo (reflectivity) of the land, due to **desertification or deforestation** will also affect the amount of solar energy absorbed, as will absorption of solar radiation (and outgoing long-wave radiation) by **aerosols** in the lower atmosphere (where they can be man-made) or the upper atmosphere (where they are predominantly natural, originating mainly from volcanoes).

The Greenhouse Effect

Apart from solar radiation itself, the most important radiative forcing arises from the **greenhouse effect.**

Short-wave solar radiation can pass through the clear atmosphere relatively unimpeded, but long-wave terrestrial radiation emitted by the warm surface of the Earth is partially absorbed and then re-emitted out to space by a number of trace gases in the cooler atmosphere above. This process adds to the net energy input to the lower atmosphere and the underlying surface thereby increasing their temperature. This is the basic greenhouse effect; the trace gases are often thought of as acting in a way somewhat analogous to the glass in a greenhouse. The main greenhouse gases are not the major constituents, nitrogen and oxygen, but water vapour (the biggest contributor), carbon dioxide, methane, nitrous oxide and (in recent years) chlorofluorocarbons.

How do we Know that the Greenhouse Effect is Real?

We know that the greenhouse effect works in practice, for several reasons. Firstly, the mean temperature of the Earth's surface is already 32°C warmer than it would be if the natural greenhouse gases (mainly carbon dioxide and water vapour) were not present. Satellite measurements of the radiation emitted from the Earth's surface and atmosphere demonstrate the absorption due to the greenhouse gases.

Secondly, we know that the composition of the atmospheres of Venus, Earth and Mars are very different, and their surface temperatures (shown in the table below) are in good agreement with those calculated on the basis of greenhouse effect theory.

Thirdly, measurements from ice cores, dating back 160,000 years, show that the Earth's temperature was closely related to the concentration of greenhouse gases in the atmosphere. The ice core record shows that the

	Surface Pressure (Relative to Earth)	Main Greenhouse Gases	Surface temperature in absence of Greenhouse effect	Observed Surface Temperature	Warming due to Greenhouse Effect
VENUS	90	> 90% CO_2	46°C	477°C	523°C
EARTH	1	~0 04% CO_2 ~1% H_2O	-18°C	15°C	33°C
MARS	0 007	> 80% CO_2	-57°C	-47°C	10°C

atmospheric levels of carbon dioxide, methane, and nitrous oxide were much lower during the ice ages than during interglacial periods It is likely that changes in greenhouse gas concentrations contributed, in part, to the large (4 - 5°C) temperature swings between ice ages and interglacial periods

The Enhanced Greenhouse Effect

An increase in concentrations of greenhouse gases is expected to raise the global-mean surface-air temperature which, for simplicity, is usually referred to as the global temperature' Strictly this is an *enhanced* greenhouse effect - above that occurring due to natural greenhouse gas concentrations The word enhanced is frequently omitted, but should not be forgotten in this context

Changes in the Abundances of the Greenhouse Gases

We know, with certainty, that the concentrations of naturally occurring greenhouse gases in the atmosphere have varied on palaeo time-scales For a thousand years prior to the industrial revolution the abundances of these gases were relatively constant However as the world s population increased, emissions of greenhouse gases such as carbon dioxide, methane, chlorofluorocarbons, nitrous oxide, and tropospheric ozone have increased substantially due to industrialisation and changes in agriculture and land-use Carbon dioxide, methane, and nitrous oxide all have significant natural and man-made sources, while the chlorofluorocarbons (CFCs) are recent man-made gases **Section 1** of the report summarises our knowledge of the various greenhouse gases, their sources, sinks and lifetimes, and their likely rate of increase

Relative Importance of Greenhouse Gases

So far as radiative forcing of the climate is concerned, the increase in carbon dioxide has been the most important (contributing about 60% of the increased forcing over the last 200 years), methane is of next importance contributing about 20%, chloroflourocarbons contribute about 10% and all the other gases the remaining 10% **Section 2** of the report reviews the contributions of the different gases to radiative forcing in more detail

Feedbacks

If everything else in the climate system remained the same following an increase in greenhouse gases, it would be relatively easy to calculate, from a knowledge of their radiative properties, what the increase in average global temperature would be However, as the components of the system begin to warm, other factors come into play which are called feedbacks These factors can act to amplify the initial warming (positive feedbacks) or reduce it (negative feedbacks) Negative feedbacks can reduce the warming but cannot produce a global cooling The simplest of these feedbacks arises because as the atmosphere warms the amount of water vapour it holds increases Water vapour is an important greenhouse gas and will therefore amplify the warming Other feedbacks occur through interactions with snow and sea-ice, with clouds and with the biosphere **Section 3** explores these more fully

The Role of the Oceans

The oceans play a central role in shaping the climate through three distinct mechanisms Firstly they absorb carbon dioxide and exchange it with the atmosphere (**Section 1** addresses this aspect of the carbon cycle) Secondly, they exchange heat water vapour and momentum with the atmosphere. Wind stress at the sea surface drives the large-scale ocean circulation. Water vapour, evaporated from the ocean surface, is transported by the atmospheric circulation and provides latent heat energy to the atmosphere. The ocean circulations in their turn redistribute heat, fresh water and dissolved chemicals around the globe. Thirdly, they sequester heat, absorbed at the surface, in the deepest regions for periods of a thousand years or more through vertical circulation and convective mixing.

Therefore, any study of the climate and how it might change must include a detailed description of processes in the ocean together with the coupling between the ocean and the atmosphere. A description of ocean processes is presented in **Section 3** and the results from ocean-atmosphere coupled models appear in **Section 6**.

Climate Forecasting

To carry out a climate forecast it is necessary to take into account all the complex interactions and feedbacks between the different components of the climate system. This is done through the use of a **numerical model** which as far as possible includes a description of all the processes and interactions. Such a model is a more elaborate version of the global models currently employed for weather forecasting.

Global forecasting models concentrate on the circulation of the atmosphere (for that reason they are often called **atmospheric general circulation models** (or atmospheric GCMs)). They are based on equations describing the atmosphere's basic dynamics, and include descriptions in simple physical terms (called parameterizations) of the physical processes. Forecasts are made for several days ahead from an analysis derived from weather observations. Such forecasts are called deterministic weather forecasts because they describe the detailed weather to be expected at any place and time on the synoptic scale (of the order of a few hundred kilometres). They cannot, of course, be deterministic so far as small scale phenomena, such as individual shower clouds, are concerned.

The most elaborate climate model employed at the present time consists of an atmospheric GCM coupled to an **ocean GCM** which describes the structure and dynamics of the ocean. Added to this coupled model are appropriate descriptions, although necessarily somewhat crude, of the other components of the climate system (namely, the land surface and the ice) and the interactions between them. If the model is run for several years with parameters and forcing appropriate to the current climate, the model's output should bear a close resemblance to the observed climate. If parameters representing, say, increasing greenhouse gases are introduced into the model, it can be used to simulate or predict the resulting climate change.

To run models such as these requires very large computer resources indeed. However, simplified models are also employed to explore the various sensitivities of the climate system and to make simulations of the time evolution of climate change. In particular, simplifications of the ocean structure and dynamics are included, details are given in **Section 3**. **Section 4** describes how well the various models simulate current climate and also how well they have been able to make reconstructions of past climates.

Equilibrium and Time-Dependent Response

The simplest way of employing a climate model to determine the response to a change in forcing due to increases in greenhouse gases is to first run the model for several years with the current forcing, then to change the forcing (for instance by doubling the concentration of carbon dioxide in the appropriate part of the model) and run the model again. Comparing the two model climates will then provide a forecast of the change in climate to be expected under the new conditions. Such a forecast will be of the **equilibrium response**, it is the response expected to that change when the whole climate system has reached a steady state. Most climate forecasting models to date have been run in this equilibrium response mode. **Section 5** summarises the results obtained from such models.

A more complicated and difficult calculation can be carried out by changing the forcing in the model slowly on the appropriate natural time-scale. Again, comparison with the unperturbed model climate is carried out to obtain the **time-dependent response** of the model to climate change.

These time-dependent models, results from which are presented in **Section 6**, are the ones which describe the climate system most realistically. However, rather few of them have been run so far. Comparison of the magnitude and patterns of climate change as predicted by these models has been made with results from models run in the equilibrium response mode. The results of this comparison provide guidance on how to interpret some of the more detailed results from the equilibrium model runs.

Detection of Climate Change

Of central importance to the study of climate and climate change are observations of climate. From the distant past we have palaeo-climatic data which provide information on the response of the climate system to different historical forcings. **Section 4** describes how climate models can be validated in these differing climate regimes. It is only within about the last hundred years, however, that accurate observations with good global coverage exist. Even so, there have been numerous changes in instruments and observational practices during this period, and quite sophisticated numerical corrections are required to standardize the data to a self consistent record

Section 7 discusses these issues and provides evidence, from land and sea temperature records and glacier measurements, that a small global warming has occurred since the late nineteenth century The temperature and precipitation records are examined regionally as well, and recent data on sea-ice and snow cover are shown

Within these time-series of data we can examine the natural variability of climate and search for a possible climate change signal due to increasing greenhouse gases **Section 8** compares the expectations from model predictions with the observed change in climate At a global level the change is consistent with predictions from models but there may be other effects producing it Problems arise at a regional level because there are differences between the various predictions and because the changes observed so far are small and comparable to spatial and temporal noise In this Section, however, an estimate is made of the likely time-scale for detection of the enhanced greenhouse effect

Changes in Sea Level

An important consequence of a rise in global temperature would be an increase in sea level **Section 9** assesses the contribution from thermal expansion of the oceans, melting of mountain glaciers and changes to the Greenland and Antarctic ice sheets under the four IPCC Scenarios of future temperature rise Measurements of sea level from tide gauges around the world date back a hundred years and provide evidence for a small increase which appears to be fairly steady The stability of the West Antarctic Ice Sheet, which has sometimes been invoked as a possible mechanism for large sea level rise in the future, is examined

Climate Change and Ecosystems

Ecosystems (both land and marine based plant-life) will respond to climate change and through feedback processes, influence it **Section 10** looks at the direct effect of climate change on crops forests and tundra Plant growth and metabolism are functions of temperature and soil moisture, as well as carbon dioxide itself, changes in the activity of ecosystems will therefore modify the carbon cycle Plant species have migrated in the past, but their ability to adapt in future may be limited by the presence of artificial barriers caused by human activities and by the speed of climate change This Section also looks at the effects of deforestation and reforestation on the global carbon budget

Improving our Predictions

Despite our confidence in the general predictions from numerical models, there will be uncertainties in the detailed timing and patterns of climate change due to the enhanced greenhouse effect for some time to come **Section 11** lists the many programs which are already underway or are planned to narrow these uncertainties These cover the full range of Earth and Space based observing systems, process studies to unravel the details of feedbacks between the many components of the climate system and expected developments in computer models

The Climate Implications of Emission Controls

In order that any policy decisions on emission controls are soundly based it is useful to quantify the climate benefits of different levels of controls on different time-scales The **Annex** to this Report shows the full pathway of emissions to temperature change and sea-level rise for the four IPCC Policy Scenarios plus four other Science Scenarios The Policy Scenarios were derived by IPCC Working Group III and assume progressively more stringent levels of emission controls The Science Scenarios were chosen artificially to illustrate the effects of sooner, rather than later, emission controls, and to show the changes in temperature and sea level which we may be committed to as a result of past emissions of greenhouse gases

References

WMO (1979) Proceedings of the World Climate Conference, Geneva, 12-23 February 1979 WMO 537

WMO (1984) Scientific Plan for the World Climate Research Program WCRP Pub series No 2, WMO/TD No 6