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The Climate System: an Overview

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1.1.1 Climate

Weather and climate

Weather and climate have a profound influence on life on Earth. They are part of the daily experience of human beings and are essential for health, food production and well-being. Many consider the prospect of human-induced climate change as a matter of concern. The IPCC Second Assessment Report (IPCC, 1996) (hereafter SAR) presented scientific evidence that human activities may already be influencing the climate. If one wishes to understand, detect and eventually predict the human influence on climate, one needs to understand the system that determines the climate of the Earth and of the processes that lead to climate change.

In common parlance the notions "weather" and "climate" are loosely defined[1]. The "weather", as we experience it, is the fluctuating state of the atmosphere around us, characterised by the temperature, wind, precipitation, clouds and other weather elements. This weather is the result of rapidly developing and decaying weather systems such as mid-latitude low and high pressure systems with their associated frontal zones, showers and tropical cyclones. Weather has only limited predictability. Mesoscale convective systems are predictable over a period of hours only; synoptic scale cyclones may be predictable over a period of several days to a week. Beyond a week or two individual weather systems are unpredictable. "Climate" refers to the average weather in terms of the mean and its variability over a certain time-span and a certain area. Classical climatology provides a classification and description of the various climate regimes found on Earth. Climate varies from place to place, depending on latitude, distance to the sea, vegetation, presence or absence of mountains or other geographical factors. Climate varies also in time; from season to season, year to year, decade to decade or on much longer time-scales, such as the Ice Ages. Statistically significant variations of the mean state of the climate or of its variability, typically persisting for decades or longer, are referred to as "climate change". The Glossary gives definitions of these important and central notions of "climate variability" and "climate change".

Climate variations and change, caused by external forcings, may be partly predictable, particularly on the larger, continental and global, spatial scales. Because human activities, such as the emission of greenhouse gases or land-use change, do result in external forcing, it is believed that the large-scale aspects of human-induced climate change are also partly predictable. However the ability to actually do so is limited because we cannot accurately predict population change, economic change, technological development, and other relevant characteristics of future human activity. In practice, therefore, one has to rely on carefully constructed scenarios of human behaviour and determine climate projections on the basis of such scenarios.

Climate variables

The traditional knowledge of weather and climate focuses on those variables that affect daily life most directly: average, maximum and minimum temperature, wind near the surface of the Earth, precipitation in its various forms, humidity, cloud type and amount, and solar radiation. These are the variables observed hourly by a large number of weather stations around the globe.

However this is only part of the reality that determines weather and climate. The growth, movement and decay of weather systems depend also on the vertical structure of the atmosphere, the influence of the underlying land and sea and many other factors not directly experienced by human beings. Climate is determined by the atmospheric circulation and by its interactions with the large-scale ocean currents and the land with its features such as albedo, vegetation and soil moisture. The climate of the Earth as a whole depends on factors that influence the radiative balance, such as for example, the atmospheric composition, solar radiation or volcanic eruptions. To understand the climate of our planet Earth and its variations and to understand and possibly predict the changes of the climate brought about by human activities, one cannot ignore any of these many factors and components that determine the climate. We must understand the *climate system*, the complicated system consisting of various components, including the dynamics and composition of the atmosphere, the ocean, the ice and snow cover, the land surface and its features, the many mutual interactions between them, and the large variety of physical, chemical and biological processes taking place in and among these components. "Climate" in a wider sense refers to the state of the climate system as a whole, including a statistical description of its variations. This chapter provides the reader with an overview of the climate system and the climate in this wider sense, and acts as an introduction to the Report.

1.1.2 The Climate System

Its components

The climate system, as defined in this Report, is an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, forced or influenced by various external forcing mechanisms, the most important of which is the Sun (see Figure 1.1). Also the direct effect of human activities on the climate system is considered an external forcing.

The *atmosphere* is the most unstable and rapidly changing part of the system. Its composition, which has changed with the evolution of the Earth, is of central importance to the problem assessed in this Report. The Earth's dry atmosphere is composed mainly of nitrogen (N_2, 78.1% volume mixing ratio), oxygen (O_2, 20.9% volume mixing ratio, and argon (Ar, 0.93% volume mixing ratio). These gases have only limited interaction with the incoming solar radiation and they do not interact with the infrared radiation emitted by the Earth. However there are a number of trace gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3), which do absorb and emit infrared radiation. These so called greenhouse gases, with a total volume mixing ratio in dry air of less than 0.1% by volume, play an essential role in the Earth's energy budget. Moreover the

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[1] For a definition of scientific and technical terms used in this Report: see Appendix I: Glossary.

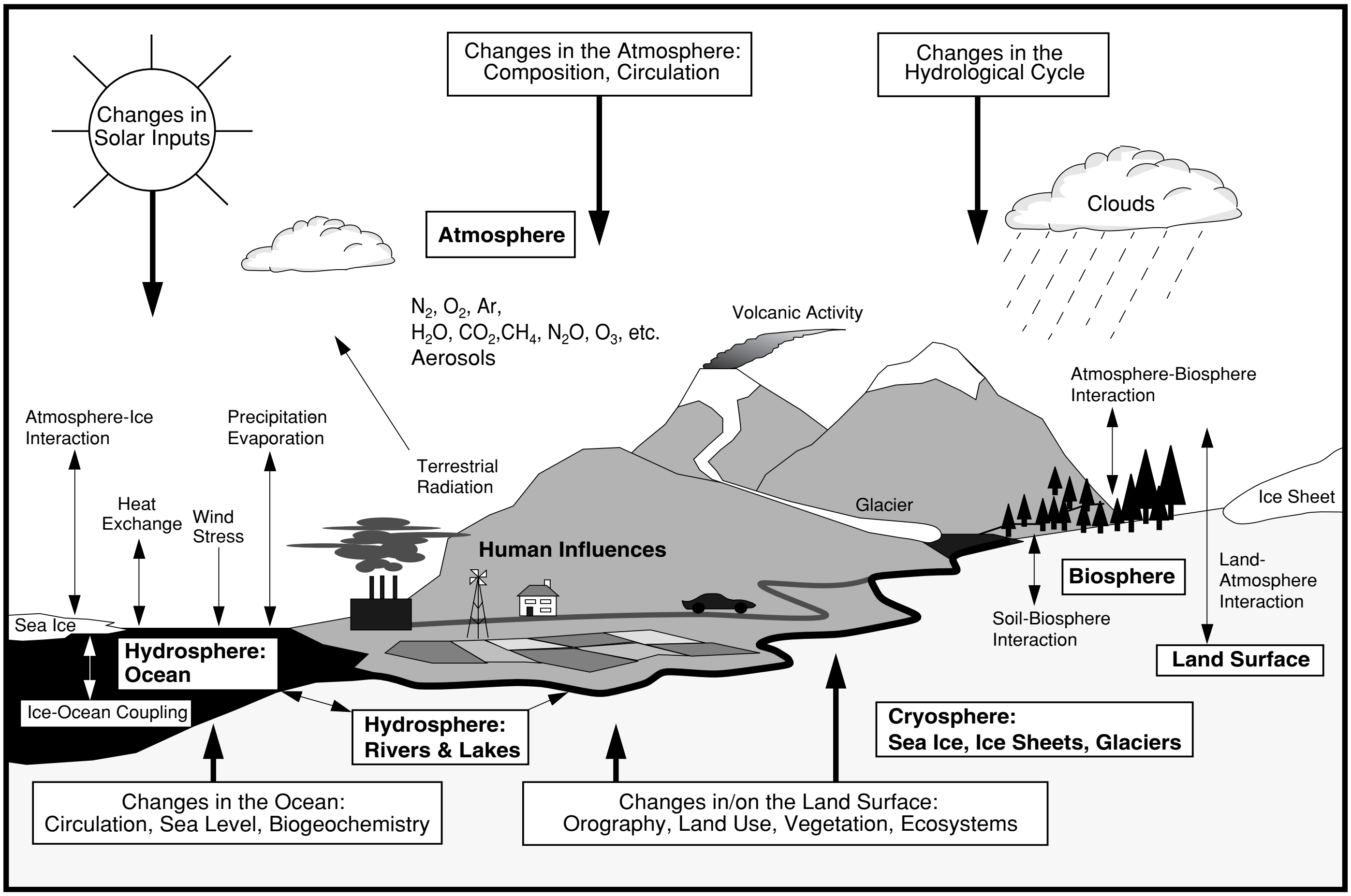

Figure 1.1: Schematic view of the components of the global climate system (bold), their processes and interactions (thin arrows) and some aspects that may change (bold arrows).

atmosphere contains water vapour (H_2O), which is also a natural greenhouse gas. Its volume mixing ratio is highly variable, but it is typically in the order of 1%. Because these greenhouse gases absorb the infrared radiation emitted by the Earth and emit infrared radiation up- and downward, they tend to raise the temperature near the Earth's surface. Water vapour, CO_2 and O_3 also absorb solar short-wave radiation.

The atmospheric distribution of ozone and its role in the Earth's energy budget is unique. Ozone in the lower part of the atmosphere, the troposphere and lower stratosphere, acts as a greenhouse gas. Higher up in the stratosphere there is a natural layer of high ozone concentration, which absorbs solar ultra-violet radiation. In this way this so-called ozone layer plays an essential role in the stratosphere's radiative balance, at the same time filtering out this potentially damaging form of radiation.

Beside these gases, the atmosphere also contains solid and liquid particles (aerosols) and clouds, which interact with the incoming and outgoing radiation in a complex and spatially very variable manner. The most variable component of the atmosphere is water in its various phases such as vapour, cloud droplets, and ice crystals. Water vapour is the strongest greenhouse gas. For these reasons and because the transition between the various phases absorb and release much energy, water vapour is central to the climate and its variability and change.

The *hydrosphere* is the component comprising all liquid surface and subterranean water, both fresh water, including rivers, lakes and aquifers, and saline water of the oceans and seas. Fresh water runoff from the land returning to the oceans in rivers influences the ocean's composition and circulation. The oceans cover approximately 70% of the Earth's surface. They store and transport a large amount of energy and dissolve and store great quantities of carbon dioxide. Their circulation, driven by the wind and by density contrasts caused by salinity and thermal gradients (the so-called thermohaline circulation), is much slower than the atmospheric circulation. Mainly due to the large thermal inertia of the oceans, they damp vast and strong temperature changes and function as a regulator of the Earth's climate and as a source of natural climate variability, in particular on the longer time-scales.

The *cryosphere*, including the ice sheets of Greenland and Antarctica, continental glaciers and snow fields, sea ice and permafrost, derives its importance to the climate system from its high reflectivity (albedo) for solar radiation, its low thermal conductivity, its large thermal inertia and, especially, its critical role in driving deep ocean water circulation. Because the ice sheets store a large amount of water, variations in their volume are a potential source of sea level variations (Chapter 11).

Vegetation and soils at the *land surface* control how energy received from the Sun is returned to the atmosphere. Some is returned as long-wave (infrared) radiation, heating the atmosphere as the land surface warms. Some serves to evaporate water, either in the soil or in the leaves of plants, bringing water back into the atmosphere. Because the evaporation of soil moisture requires energy, soil moisture has a strong influence on the surface temperature. The texture of the land surface (its roughness) influences the atmosphere dynamically as winds blow over the land's surface. Roughness is determined by both topography and vegetation. Wind also blows dust from the surface into the atmosphere, which interacts with the atmospheric radiation.

The marine and terrestrial *biospheres* have a major impact on the atmosphere's composition. The biota influence the uptake and release of greenhouse gases. Through the photosynthetic process, both marine and terrestrial plants (especially forests) store significant amounts of carbon from carbon dioxide. Thus, the biosphere plays a central role in the carbon cycle, as well as in the budgets of many other gases, such as methane and nitrous oxide. Other biospheric emissions are the so-called volatile organic compounds (VOC) which may have important effects on atmospheric chemistry, on aerosol formation and therefore on climate. Because the storage of carbon and the exchange of trace gases are influenced by climate, feedbacks between climate change and atmospheric concentrations of trace gases can occur. The influence of climate on the biosphere is preserved as fossils, tree rings, pollen and other records, so that much of what is known of past climates comes from such biotic indicators.

Interactions among the components

Many physical, chemical and biological interaction processes occur among the various components of the climate system on a wide range of space and time scales, making the system extremely complex. Although the components of the climate system are very different in their composition, physical and chemical properties, structure and behaviour, they are all linked by fluxes of mass, heat and momentum: all subsystems are open and interrelated.

As an example, the atmosphere and the oceans are strongly coupled and exchange, among others, water vapour and heat through evaporation. This is part of the hydrological cycle and leads to condensation, cloud formation, precipitation and runoff, and supplies energy to weather systems. On the other hand, precipitation has an influence on salinity, its distribution and the thermohaline circulation. Atmosphere and oceans also exchange, among other gases, carbon dioxide, maintaining a balance by dissolving it in cold polar water which sinks into the deep ocean and by outgassing in relatively warm upwelling water near the equator.

Some other examples: sea ice hinders the exchanges between atmosphere and oceans; the biosphere influences the carbon dioxide concentration by photosynthesis and respiration, which in turn is influenced by climate change. The biosphere also affects the input of water in the atmosphere through evapotranspiration, and the atmosphere's radiative balance through the amount of sunlight reflected back to the sky (albedo).

These are just a few examples from a virtually inexhaustible list of complex interactions some of which are poorly known or perhaps even unknown. Chapter 7 provides an assessment of the present knowledge of physical climate processes and feedbacks, whilst Chapter 3 deals with biological feedbacks.

Any change, whether natural or anthropogenic, in the components of the climate system and their interactions, or in the external forcing, may result in climate variations. The following sections introduce various aspects of natural climate variations, followed by an introduction to the human influence on the climate system.

1.2 Natural Climate Variations

1.2.1 Natural Forcing of the Climate System

The Sun and the global energy balance

The ultimate source of energy that drives the climate system is radiation from the Sun. About half of the radiation is in the visible short-wave part of the electromagnetic spectrum. The other half is mostly in the near-infrared part, with some in the ultraviolet part of the spectrum. Each square metre of the Earth's spherical surface outside the atmosphere receives an average throughout the year of 342 Watts of solar radiation, 31% of which is immediately reflected back into space by clouds, by the atmosphere, and by the Earth's surface. The remaining 235 Wm^{-2} is partly absorbed by the atmosphere but most (168 Wm^{-2}) warms the Earth's surface: the land and the ocean. The Earth's surface returns that heat to the atmosphere, partly as infrared radiation, partly as sensible heat and as water vapour which releases its heat when it condenses higher up in the atmosphere. This exchange of energy between surface and atmosphere maintains under present conditions a global mean temperature near the surface of 14°C, decreasing rapidly with height and reaching a mean temperature of –58°C at the top of the troposphere.

For a stable climate, a balance is required between incoming solar radiation and the outgoing radiation emitted by the climate system. Therefore the climate system itself must radiate on average 235 Wm^{-2} back into space. Details of this energy balance can be seen in Figure 1.2, which shows on the left hand side what happens with the incoming solar radiation, and on the right hand side how the atmosphere emits the outgoing infrared radiation. Any physical object radiates energy of an amount and at wavelengths typical for the temperature of the object: at higher temperatures more energy is radiated at shorter wavelengths. For the Earth to radiate 235 Wm^{-2}, it should radiate at an effective emission temperature of −19°C with typical wavelengths in the infrared part of the spectrum. This is 33°C lower than the average temperature of 14°C at the Earth's surface. To understand why this is so, one must take into account the radiative properties of the atmosphere in the infrared part of the spectrum.

The natural greenhouse effect

The atmosphere contains several trace gases which absorb and emit infrared radiation. These so-called greenhouse gases absorb infrared radiation, emitted by the Earth's surface, the atmosphere

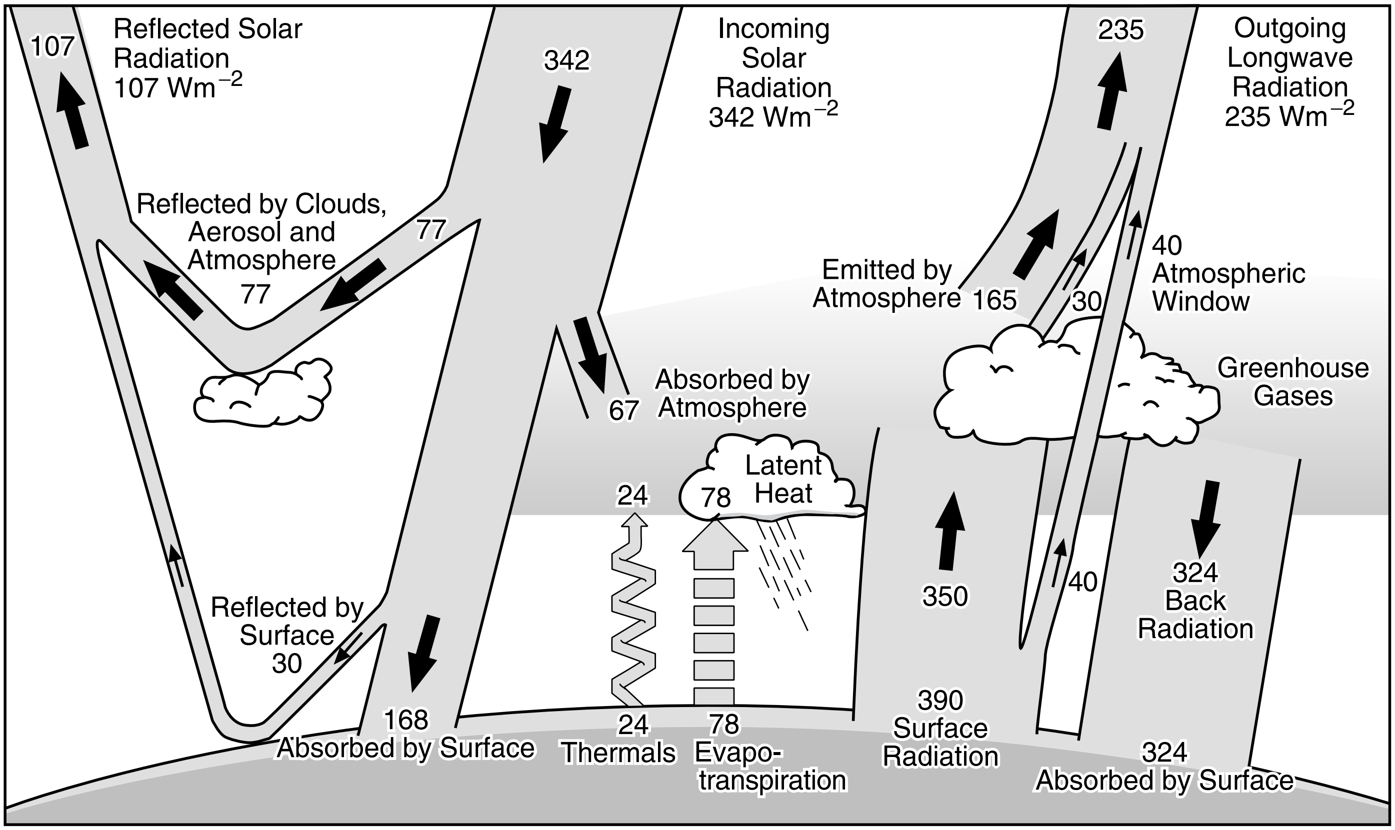

Figure 1.2: The Earth's annual and global mean energy balance. Of the incoming solar radiation, 49% (168 Wm^{-2}) is absorbed by the surface. That heat is returned to the atmosphere as sensible heat, as evapotranspiration (latent heat) and as thermal infrared radiation. Most of this radiation is absorbed by the atmosphere, which in turn emits radiation both up and down. The radiation lost to space comes from cloud tops and atmospheric regions much colder than the surface. This causes a greenhouse effect. Source: Kiehl and Trenberth, 1997: Earth's Annual Global Mean Energy Budget, *Bull. Am. Met. Soc*. 78, 197-208.

and clouds, except in a transparent part of the spectrum called the "atmospheric window", as shown in Figure 1.2. They emit in turn infrared radiation in all directions including downward to the Earth's surface. Thus greenhouse gases trap heat within the atmosphere. This mechanism is called the natural greenhouse effect. The net result is an upward transfer of infrared radiation from warmer levels near the Earth's surface to colder levels at higher altitudes. The infrared radiation is effectively radiated back into space from an altitude with a temperature of, on average, −19°C, in balance with the incoming radiation, whereas the Earth's surface is kept at a much higher temperature of on average 14°C. This effective emission temperature of −19°C corresponds in mid-latitudes with a height of approximately 5 km. Note that it is essential for the greenhouse effect that the temperature of the lower atmosphere is not constant (isothermal) but decreases with height. The natural greenhouse effect is part of the energy balance of the Earth, as can be seen schematically in Figure 1.2.

Clouds also play an important role in the Earth's energy balance and in particular in the natural greenhouse effect. Clouds absorb and emit infrared radiation and thus contribute to warming the Earth's surface, just like the greenhouse gases. On the other hand, most clouds are bright reflectors of solar radiation and tend to cool the climate system. The net average effect of the Earth's cloud cover in the present climate is a slight cooling: the reflection of radiation more than compensates for the greenhouse effect of clouds. However this effect is highly variable, depending on height, type and optical properties of clouds.

This introduction to the global energy balance and the natural greenhouse effect is entirely in terms of the global mean and in radiative terms. However, for a full understanding of the greenhouse effect and of its impact on the climate system, dynamical feedbacks and energy transfer processes should also be taken into account. Chapter 7 presents a more detailed analysis and assessment.

Radiative forcing and forcing variability

In an equilibrium climate state the average net radiation at the top of the atmosphere is zero. A change in either the solar radiation or the infrared radiation changes the net radiation. The corresponding imbalance is called "radiative forcing". In practice, for this purpose, the top of the troposphere (the tropopause) is taken as the top of the atmosphere, because the stratosphere adjusts in a matter of months to changes in the radiative balance, whereas the surface-troposphere system adjusts much more slowly, owing principally to the large thermal inertia of the oceans. The radiative forcing of the surface troposphere system is then the change in net irradiance at the tropopause after allowing for stratospheric temperatures to re-adjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values. A detailed explanation and discussion of the radiative forcing concept may be found in Appendix 6.1 to Chapter 6.

External forcings, such as the solar radiation or the large amounts of aerosols ejected by volcanic eruption into the atmosphere, may vary on widely different time-scales, causing natural variations in the radiative forcing. These variations may be negative or positive. In either case the climate system must react to restore the balance. A positive radiative forcing tends to warm the surface on average, whereas a negative radiative forcing tends to cool it. Internal climate processes and feedbacks may also cause variations in the radiative balance by their impact on the reflected solar radiation or emitted infrared radiation, but such variations are not considered part of radiative forcing. Chapter 6 assesses the present knowledge of radiative forcing and its variations, including the anthropogenic change of the atmospheric composition.

1.2.2 Natural Variability of Climate

Internally and externally induced climate variability

Climate variations, both in the mean state and in other statistics such as, for example, the occurrence of extreme events, may result from radiative forcing, but also from internal interactions between components of the climate system. A distinction can therefore be made between externally and internally induced natural climate variability and change.

When variations in the external forcing occur, the response time of the various components of the climate system is very different. With regard to the atmosphere, the response time of the troposphere is relatively short, from days to weeks, whereas the stratosphere comes into equilibrium on a time-scale of typically a few months. Due to their large heat capacity, the oceans have a much longer response time, typically decades but up to centuries or millennia. The response time of the strongly coupled surface-troposphere system is therefore slow compared with that of the stratosphere, and is mainly determined by the oceans. The biosphere may respond fast, e.g. to droughts, but also very slowly to imposed changes. Therefore the system may respond to variations in external forcing on a wide range of space- and time-scales. The impact of solar variations on the climate provides an example of such externally induced climate variations.

But even without changes in external forcing, the climate may vary naturally, because, in a system of components with very different response times and non-linear interactions, the components are never in equilibrium and are constantly varying. An example of such internal climate variation is the El Niño-Southern Oscillation (ENSO), resulting from the interaction between atmosphere and ocean in the tropical Pacific.

Feedbacks and non-linearities

The response of the climate to the internal variability of the climate system and to external forcings is further complicated by feedbacks and non-linear responses of the components. A process is called a feedback when the result of the process affects its origin thereby intensifying (positive feedback) or reducing (negative feedback) the original effect. An important example of a positive feedback is the water vapour feedback in which the amount of water vapour in the atmosphere increases as the Earth warms. This increase in turn may amplify the warming because water vapour is a strong greenhouse gas. A strong and very basic negative feedback is radiative damping: an increase in temperature strongly increases the amount of emitted infrared radiation. This limits and controls the original temperature increase.

A distinction is made between physical feedbacks involving physical climate processes, and biogeochemical feedbacks often involving coupled biological, geological and chemical processes. An example of a physical feedback is the complicated interaction between clouds and the radiative balance. Chapter 7 provides an overview and assessment of the present knowledge of such feedbacks. An important example of a biogeochemical feedback is the interaction between the atmospheric CO_2 concentration and the carbon uptake by the land surface and the oceans. Understanding this feedback is essential for an understanding of the carbon cycle. This is discussed and assessed in detail in Chapter 3.

Many processes and interactions in the climate system are non-linear. That means that there is no simple proportional relation between cause and effect. A complex, non-linear system may display what is technically called chaotic behaviour. This means that the behaviour of the system is critically dependent on very small changes of the initial conditions. This does not imply, however, that the behaviour of non-linear chaotic systems is entirely unpredictable, contrary to what is meant by "chaotic" in colloquial language. It has, however, consequences for the nature of its variability and the predictability of its variations. The daily weather is a good example. The evolution of weather systems responsible for the daily weather is governed by such non-linear chaotic dynamics. This does not preclude successful weather prediction, but its predictability is limited to a period of at most two weeks. Similarly, although the climate system is highly non-linear, the quasi-linear response of many models to present and predicted levels of external radiative forcing suggests that the large-scale aspects of human-induced climate change may be predictable, although as discussed in Section 1.3.2 below, unpredictable behaviour of non-linear systems can never be ruled out. The predictability of the climate system is discussed in Chapter 7.

Global and hemispheric variability

Climate varies naturally on all time-scales. During the last million years or so, glacial periods and interglacials have alternated as a result of variations in the Earth's orbital parameters. Based on Antarctic ice cores, more detailed information is available now about the four full glacial cycles during the last 500,000 years. In recent years it was discovered that during the last glacial period large and very rapid temperature variations took place over large parts of the globe, in particular in the higher latitudes of the Northern Hemisphere. These abrupt events saw temperature changes of many degrees within a human lifetime. In contrast, the last 10,000 years appear to have been relatively more stable, though locally quite large changes have occurred.

Recent analyses suggest that the Northern Hemisphere climate of the past 1,000 years was characterised by an irregular but steady cooling, followed by a strong warming during the 20th century. Temperatures were relatively warm during the 11th to 13th centuries and relatively cool during the 16th to 19th centuries. These periods coincide with what are traditionally known as the medieval Climate Optimum and the Little Ice Age, although these anomalies appear to have been most distinct only in and around the North Atlantic region. Based on these analyses, the warmth of the late 20th century appears to have been unprecedented during the millennium. A comprehensive review and assessment of observed global and hemispheric variability may be found in Chapter 2.

The scarce data from the Southern Hemisphere suggest temperature changes in past centuries markedly different from those in the Northern Hemisphere, the only obvious similarity being the strong warming during the 20th century.

Regional patterns of climate variability

Regional or local climate is generally much more variable than climate on a hemispheric or global scale because regional or local variations in one region are compensated for by opposite variations elsewhere. Indeed a closer inspection of the spatial structure of climate variability, in particular on seasonal and longer time-scales, shows that it occurs predominantly in preferred large-scale and geographically anchored spatial patterns. Such patterns result from interactions between the atmospheric circulation and the land and ocean surfaces. Though geographically anchored, their amplitude can change in time as, for example, the heat exchange with the underlying ocean changes.

A well-known example is the quasi-periodically varying ENSO phenomenon, caused by atmosphere-ocean interaction in the tropical Pacific. The resulting El Niño and La Niña events have a worldwide impact on weather and climate.

Another example is the North Atlantic Oscillation (NAO), which has a strong influence on the climate of Europe and part of Asia. This pattern consists of opposing variations of barometric pressure near Iceland and near the Azores. On average, a westerly current, between the Icelandic low pressure area and the Azores high-pressure area, carries cyclones with their associated frontal systems towards Europe. However the pressure difference between Iceland and the Azores fluctuates on time-scales of days to decades, and can be reversed at times. The variability of NAO has considerable influence on the regional climate variability in Europe, in particular in wintertime. Chapter 7 discusses the internal processes involved in NAO variability.

Similarly, although data are scarcer, leading modes of variability have been identified over the Southern Hemisphere. Examples are a North-South dipole structure over the Southern Pacific, whose variability is strongly related to ENSO variability, and the Antarctic Oscillation, a zonal pressure fluctuation between middle and high latitudes of the Southern Hemisphere. A detailed account of regional climate variability may be found in Chapter 2.

1.2.3 Extreme Events

Climate as defined is associated with a certain probability distribution of weather events. Weather events with values far away from the mean (such as heat waves, droughts and flooding) are by definition less likely to occur. The least likely events in a statistical sense are called "extreme events". Extreme weather in one region (e.g. a heat wave) may be normal in another. In both regions nature and society are adapted to the regional weather averaged over longer periods, but much less to extremes. For example, tropical African temperatures could severely damage vegetation or human health if they occurred in Northern Europe. Impacts of extreme events are felt strongly by ecosystems and society and may be destructive.

Small changes in climate may, but will not necessarily, have a large impact on the probability distribution of weather events in space and time, and on the intensity of extremes. Nature and society are often particularly ill prepared and vulnerable for such changes. This is the reason why since the SAR much more attention has been paid to observed and projected variations of extremes. Chapter 2 gives an assessment of the present knowledge.

1.3 Human-induced Climate Variations

1.3.1 Human Influence on the Climate System

Human beings, like other living organisms, have always influenced their environment. It is only since the beginning of the Industrial Revolution, mid-18th century, that the impact of human activities has begun to extend to a much larger scale, continental or even global. Human activities, in particular those involving the combustion of fossil fuels for industrial or domestic usage, and biomass burning, produce greenhouse gases and aerosols which affect the composition of the atmosphere. The emission of chlorofluorocarbons (CFCs) and other chlorine and bromine compounds has not only an impact on the radiative forcing, but has also led to the depletion of the stratospheric ozone layer. Land-use change, due to urbanisation and human forestry and agricultural practices, affect the physical and biological properties of the Earth's surface. Such effects change the radiative forcing and have a potential impact on regional and global climate.

Anthropogenic perturbation of the atmospheric composition

For about a thousand years before the Industrial Revolution, the amount of greenhouse gases in the atmosphere remained relatively constant. Since then, the concentration of various greenhouse gases has increased. The amount of carbon dioxide, for example, has increased by more than 30% since pre-industrial times and is still increasing at an unprecedented rate of on average 0.4% per year, mainly due to the combustion of fossil fuels and deforestation. We know that this increase is anthropogenic because the changing isotopic composition of the atmospheric CO_2 betrays the fossil origin of the increase. The concentration of other natural radiatively active atmospheric components, such as methane and nitrous oxide, is increasing as well due to agricultural, industrial and other activities. The concentration of the nitrogen oxides (NO and NO_2) and of carbon monoxide (CO) are also increasing. Although these gases are not greenhouse gases, they play a role in the atmospheric chemistry and have led to an increase in tropospheric ozone, a greenhouse gas, by 40% since pre-industrial times (Chapter 4). Moreover,

NO_2 is an important absorber of visible solar radiation. Chlorofluorocarbons and some other halogen compounds do not occur naturally in the atmosphere but have been introduced by human activities. Beside their depleting effect on the stratospheric ozone layer, they are strong greenhouse gases. Their greenhouse effect is only partly compensated for by the depletion of the ozone layer which causes a negative forcing of the surface-troposphere system. All these gases, except tropospheric ozone and its precursors, have long to very long atmospheric lifetimes and therefore become well-mixed throughout the atmosphere.

Human industrial, energy related, and land-use activities also increase the amount of aerosol in the atmosphere, in the form of mineral dust, sulphates and nitrates and soot. Their atmospheric lifetime is short because they are removed by rain. As a result their concentrations are highest near their sources and vary substantially regionally, with global consequences. The increases in greenhouse gas concentrations and aerosol content in the atmosphere result in a change in the radiative forcing to which the climate system must act to restore the radiative balance.

The enhanced greenhouse effect

The increased concentration of greenhouse gases in the atmosphere enhances the absorption and emission of infrared radiation. The atmosphere's opacity increases so that the altitude from which the Earth's radiation is effectively emitted into space becomes higher. Because the temperature is lower at higher altitudes, less energy is emitted, causing a positive radiative forcing. This effect is called the enhanced greenhouse effect, which is discussed in detail in Chapter 6.

If the amount of carbon dioxide were doubled instantaneously, with everything else remaining the same, the outgoing infrared radiation would be reduced by about 4 Wm^{-2}. In other words, the radiative forcing corresponding to a doubling of the CO_2 concentration would be 4 Wm^{-2}. To counteract this imbalance, the temperature of the surface-troposphere system would have to increase by 1.2°C (with an accuracy of ±10%), in the absence of other changes. In reality, due to feedbacks, the response of the climate system is much more complex. It is believed that the overall effect of the feedbacks amplifies the temperature increase to 1.5 to 4.5°C. A significant part of this uncertainty range arises from our limited knowledge of clouds and their interactions with radiation. To appreciate the magnitude of this temperature increase, it should be compared with the global mean temperature difference of perhaps 5 or 6°C from the middle of the last Ice Age to the present interglacial.

The so-called water vapour feedback, caused by an increase in atmospheric water vapour due to a temperature increase, is the most important feedback responsible for the amplification of the temperature increase. Concern has been expressed about the strength of this feedback, in particular in relation to the role of upper tropospheric humidity. Since the SAR, thinking about this feedback has become increasingly sophisticated thanks both to modelling and to observational studies. Feedbacks are discussed and assessed in Chapter 7. In particular, the present state of knowledge of the water vapour feedback is examined in Section 7.2.1.

It has been suggested that the absorption by CO_2 is already saturated so that an increase would have no effect. This, however, is not the case. Carbon dioxide absorbs infrared radiation in the middle of its 15 μm band to the extent that radiation in the middle of this band cannot escape unimpeded: this absorption is saturated. This, however, is not the case for the band's wings. It is because of these effects of partial saturation that the radiative forcing is not proportional to the increase in the carbon dioxide concentration but shows a logarithmic dependence. Every further doubling adds an additional 4 Wm^{-2} to the radiative forcing.

The other human-made greenhouse gases add to the effect of increased carbon dioxide. Their total effect at the surface is often expressed in terms of the effect of an equivalent increase in carbon dioxide.

The effect of aerosols

The effect of the increasing amount of aerosols on the radiative forcing is complex and not yet well known. The direct effect is the scattering of part of the incoming solar radiation back into space. This causes a negative radiative forcing which may partly, and locally even completely, offset the enhanced greenhouse effect. However, due to their short atmospheric lifetime, the radiative forcing is very inhomogeneous in space and in time. This complicates their effect on the highly non-linear climate system. Some aerosols, such as soot, absorb solar radiation directly, leading to local heating of the atmosphere, or absorb and emit infrared radiation, adding to the enhanced greenhouse effect.

Aerosols may also affect the number, density and size of cloud droplets. This may change the amount and optical properties of clouds, and hence their reflection and absorption. It may also have an impact on the formation of precipitation. As discussed in Chapter 5, these are potentially important indirect effects of aerosols, resulting probably in a negative radiative forcing of as yet very uncertain magnitude.

Land-use change

The term "land-use change" refers to a change in the use or management of land. Such change may result from various human activities such as changes in agriculture and irrigation, deforestation, reforestation and afforestation, but also from urbanisation or traffic. Land-use change results in changing the physical and biological properties of the land surface and thus the climate system.

It is now recognized that land-use change on the present scale may contribute significantly to changing the local, regional or even global climate and moreover has an important impact on the carbon cycle. Physical processes and feedbacks caused by land-use change, that may have an impact on the climate, include changes in albedo and surface roughness, and the exchange between land and atmosphere of water vapour and greenhouse gases. These climatic consequences of land-use change are discussed and evaluated in Section 4 of Chapter 7. Land-use change may also affect the climate system through biological processes and feedbacks involving the terrestrial vegetation, which may lead to changes in the sources and sinks of carbon in its various forms. Chapter 3 reviews the consequences for the carbon cycle. Obviously the combined effect of these physical and biogeochemical processes and feedbacks is complex, but new data sets and models start to shed light on this.

Urbanisation is another kind of land-use change. This may affect the local wind climate through its influence on the surface roughness. It may also create a local climate substantially warmer than the surrounding countryside by the heat released by densely populated human settlements, by changes in evaporation characteristics and by modifying the outgoing long-wave radiation through interception by tall buildings etc. This is known as an "urban heat island". The influence on the regional climate may be noticeable but small. It may however have a significant influence on long instrumental temperature records from stations affected by expanding urbanisation. The consequences of this urbanisation effect for the global surface temperature record has been the subject of debate. It is discussed in Section 2.2.2 of Chapter 2.

Climate response

The increase in greenhouse gas and aerosol concentrations in the atmosphere and also land-use change produces a radiative forcing or affects processes and feedbacks in the climate system. As discussed in Chapter 7, the response of the climate to these human-induced forcings is complicated by such feedbacks, by the strong non-linearity of many processes and by the fact that the various coupled components of the climate system have very different response times to perturbations. Qualitatively, an increase of atmospheric greenhouse gas concentrations leads to an average increase of the temperature of the surface-troposphere system. The response of the stratosphere is entirely different. The stratosphere is characterised by a radiative balance between absorption of solar radiation, mainly by ozone, and emission of infrared radiation mainly by carbon dioxide. An increase in the carbon dioxide concentration therefore leads to an increase of the emission and thus to a cooling of the stratosphere.

The only means available to quantify the non-linear climate response is by using numerical models of the climate system based on well-established physical, chemical and biological principles, possibly combined with empirical and statistical methods.

1.3.2 Modelling and Projection of Anthropogenic Climate Change

Climate models

The behaviour of the climate system, its components and their interactions, can be studied and simulated using tools known as climate models. These are designed mainly for studying climate processes and natural climate variability, and for projecting the response of the climate to human-induced forcing. Each component or coupled combination of components of the climate system can be represented by models of varying complexity.

The nucleus of the most complex atmosphere and ocean models, called General Circulation Models (Atmospheric General Circulation Models (AGCMs) and Ocean General Circulation Models (OGCMs)) is based upon physical laws describing the dynamics of atmosphere and ocean, expressed by mathematical equations. Since these equations are non-linear, they need to be solved numerically by means of well-established mathematical techniques. Current atmosphere models are solved spatially on a three-dimensional grid of points on the globe with a horizontal resolution typically of 250 km and some 10 to 30 levels in the vertical. A typical ocean model has a horizontal resolution of 125 to 250 km and a resolution of 200 to 400 m in the vertical. Their time-dependent behaviour is computed by taking time steps typically of 30 minutes. The impact of the spatial resolution on the model simulations is discussed in Section 8.9 of Chapter 8.

Models of the various components of the climate system may be coupled to produce increasingly complex models. The historical development of such coupled climate models is shown in Box 3 of the Technical Summary. Processes taking place on spatial and temporal scales smaller than the model's resolution, such as individual clouds or convection in atmosphere models, or heat transport through boundary currents or mesoscale eddies in ocean models, are included through a parametric representation in terms of the resolved basic quantities of the model. Coupled atmosphere-ocean models, including such parametrized physical processes, are called Atmosphere-Ocean General Circulation Models (AOGCMs). They are combined with mathematical representations of other components of the climate system, sometimes based on empirical relations, such as the land surface and the cryosphere. The most recent models may include representations of aerosol processes and the carbon cycle, and in the near future perhaps also the atmospheric chemistry. The development of these very complex coupled models goes hand in hand with the availability of ever larger and faster computers to run the models. Climate simulations require the largest, most capable computers available.

A realistic representation of the coupling between the various components of the climate system is essential. In particular the coupling between the atmosphere and the oceans is of central importance. The oceans have a huge heat capacity and a decisive influence on the hydrological cycle of the climate system, and store and exchange large quantities of carbon dioxide. To a large degree the coupling between oceans and atmosphere determines the energy budget of the climate system. There have been difficulties modelling this coupling with enough accuracy to prevent the model climate unrealistically drifting away from the observed climate. Such climate drift may be avoided by adding an artificial correction to the coupling, the so-called "flux adjustment". The evaluation in Chapter 8 of recent model results identifies improvements since the SAR, to the point that there is a reduced reliance on such corrections, with some recent models operating with minimal or no adjustment.

For various reasons, discussed in Section 8.3 of Chapter 8, it is important to also develop and use simpler models than the fully coupled comprehensive AOGCMs, for example to study only one or a specific combination of components of the climate system or even single processes, or to study many different alternatives, which is not possible or is impractical with comprehensive models. In IPCC (1997) a hierarchy of models used in the IPCC assessment process was identified and described, differing in such aspects as the number of spatial dimensions, the extent to which physical processes are explicitly represented, the level to which empirical parametrization is involved, and the computational costs of running the models. In the IPCC context, simple models are also used to compute the consequences of greenhouse gas emission scenarios. Such models are tuned to the AOGCMs to give similar results when globally averaged.

Projections of climate change

Climate models are used to simulate and quantify the climate response to present and future human activities. The first step is to simulate the present climate for extended simulation periods, typically many decades, under present conditions without any change in external climate forcing.

The quality of these simulations is assessed by systematically comparing the simulated climate with observations of the present climate. In this way the model is evaluated and its quality established. A range of diagnostic tools has been developed to assist the scientists in carrying out the evaluation. This step is essential to gain confidence in and provide a baseline for projections of human-induced climate change. Models may also be evaluated by running them under different palaeoclimate (e.g. Ice Age) conditions. Chapter 8 of this report presents a detailed assessment of the latest climate models of various complexity, in particular the AOGCMs. Once the quality of the model is established, two different strategies have been applied to make projections of future climate change.

The first, so-called equilibrium method is to change, e.g. double, the carbon dioxide concentration and to run the model again to a new equilibrium. The differences between the climate statistics of the two simulations provide an estimate of the climate change corresponding to the doubling of carbon dioxide, and of the sensitivity of the climate to a change in the radiative forcing. This method reduces systematic errors present in both simulations. If combined with simple slab ocean models, this strategy is relatively cheap because it does not require long runs to reach equilibrium. However it does not provide insight in to the time dependence of climate change.

The second, so-called transient, method, common nowadays with improved computer resources, is to force the model with a greenhouse gas and aerosol scenario. The difference between such simulation and the original baseline simulation provides a time-dependent projection of climate change.

This transient method requires a time-dependent profile of greenhouse gas and aerosol concentrations. These may be derived from so-called emission scenarios. Such scenarios have been developed, among others by IPCC, on the basis of various internally coherent assumptions concerning future socio-economic and demographic developments. In the SAR the IPCC Scenarios IS92 were used (IPCC, 1994). The most recent IPCC emission scenarios are described in the IPCC Special Report on Emission Scenarios (Nakićenović *et al.*, 2000). Different assumptions concerning e.g. the growth of the world population, energy intensity and efficiency, and economic growth, lead to considerably different emission scenarios. For example the two extreme estimates in the IPCC IS92 scenarios of the carbon dioxide emission by 2100 differ by a factor of 7. Because scenarios by their very nature should not be used and regarded as predictions, the term “climate projections” is used in this Report.

Transient simulations may also be based on artificially constructed, so-called idealised, scenarios. For example, scenarios have been constructed, assuming a gradual increase of greenhouse gas concentrations followed by stabilisation at various levels. Climate simulations based on such idealised scenarios may provide insight in to the climate response to potential policy measures leading to a stabilisation of the GHG concentrations, which is the ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC) as formulated in its Article 2. See Section 3 of Chapter 9 for an assessment.

Projections from present models show substantial agreement, but at the same time there is still a considerable degree of ambiguity and difference between the various models. All models show an increase in the globally averaged equilibrium surface temperature and global mean precipitation. In Chapter 9 the results of various models and intercomparison projects are assessed. Model results are more ambiguous about the spatial patterns of climate change than about the global response. Regional patterns depend significantly on the time dependence of the forcing, the spatial distribution of aerosol concentrations and details of the modelled climate processes. Research tools have been developed to generate more reliable regional climate information. These tools and their results are presented and assessed in Chapter 10.

To study the impact of climate change, a plausible and consistent description of a possible future climate is required. The construction of such climate change scenarios relies mainly on results from model projections, although sometimes information from past climates is used. The basis for and development of such scenarios is assessed in Chapter 13. Global and regional sea-level change scenarios are reviewed in Chapter 11.

Predictability, global and regional

In trying to quantify climate change, there is a fundamental question to be answered: is the evolution of the state of the climate system predictable? Since the pioneering work by Lorenz in the 1960s, it is well known that complex non-linear systems have limited predictability, even though the mathematical equations describing the time evolution of the system are perfectly deterministic.

The climate system is, as we have seen, such a non-linear complex system with many inherent time scales. Its predictability may depend on the type of climate event considered, the time and space scales involved and whether internal variability of the system or variability from changes in external forcing is involved. Internal variations caused by the chaotic dynamics of the climate system may be predictable to some extent. Recent experience has shown that the ENSO phenomenon may possess a fair degree of predictability for several months or even a year ahead. The same may be true for other events dominated by the long oceanic time-scales, such as perhaps the NAO. On the other hand, it is not known, for example, whether the rapid climate changes observed during the last glacial period are at all predictable or are unpredictable consequences of small changes resulting in major climatic shifts.

There is evidence to suggest that climate variations on a global scale resulting from variations in external forcing are partly predictable. Examples are the mean annual cycle and short-term climate variations from individual volcanic eruptions, which models simulate well. Regularities in past climates, in particular the cyclic succession of warm and glacial periods forced by geometrical changes in the Sun-Earth orbit, are simulated by simple models with a certain degree of success. The global and continental scale aspects of human-induced climate change, as simulated by the models forced by increasing greenhouse gas concentration, are largely reproducible. Although this is not an absolute proof, it provides evidence that such externally forced climate change may be predictable, if their forcing mechanisms are known or can be predicted.

Finally, global or continental scale climate change and variability may be more predictable than regional or local scale change, because the climate on very large spatial scales is less influenced by internal dynamics, whereas regional and local climate is much more variable under the influence of the internal chaotic dynamics of the system. See Chapter 7 for an assessment of the predictability of the climate system.

Rapid climate change

A non-linear system such as the climate system may exhibit rapid climate change as a response to internal processes or rapidly changing external forcing. Because the probability of their occurrence may be small and their predictability limited, they are colloquially referred to as “unexpected events” or “surprises”. The abrupt events that took place during the last glacial cycle are often cited as an example to demonstrate the possibility of such rapid climate change. Certain possible abrupt events as a result of the rapidly increasing anthropogenic forcing could be envisioned. Examples are a possible reorganization of the thermohaline ocean circulation in the North Atlantic resulting in a more southerly course of the Gulf Stream, which would have a profound influence on the climate of Western Europe, a possible reduction of upper-level ocean cycling in the Southern Ocean, or a possible but unlikely rapid disintegration of part of the Antarctic ice sheet with dramatic consequences for the global sea level.

More generally, with a rapidly changing external forcing, the non-linear climate system may experience as yet unenvisionable, unexpected, rapid change. Chapter 7, in particular Section 7.7, of this Report reviews and assesses the present knowledge of non-linear events and rapid climate change. Potential rapid changes in sea level are assessed in Chapter 11.

1.3.3 Observing Anthropogenic Climate Change

Observing the climate

The question naturally arises whether the system has already undergone human-induced climate change. To answer this question, accurate and detailed observations of climate and climate variability are required. Instrumental observations of land and ocean surface weather variables and sea surface temperature have been made increasingly widely since the mid-19th century. Recently, ships’ observations have been supplemented by data from dedicated buoys. The network of upper-air observations, however, only became widespread in the late 1950s. The density of observing stations always has been and still is extremely inhomogeneous, with many stations in densely populated areas and virtually none in huge oceanic areas. In recent times special earth-observation satellites have been launched, providing a wide range of observations of various components of the climate system all over the globe. The correct interpretation of such data still requires high quality *in situ* and surface data. The longer observational records suffer from changes in instrumentation, measurement techniques, exposure and gaps due to political circumstances or wars. Satellite data also require compensation for orbital and atmospheric transmission effects and for instrumental biases and instabilities. Earlier the problems related to urbanisation were mentioned. To be useful for the detection of climate change, observational records have to be adjusted carefully for all these effects.

Concern has been expressed about the present condition of the observational networks. The number of upper-air observations, surface stations and observations from ships is declining, partly compensated for by an increasing number of satellite observations. An increasing number of stations are being automated, which may have an impact on the quality and homogeneity of the observations. Maintaining and improving the quality and density of existing observational networks is essential for necessary high standard information. In order to implement and improve systematic observations of all components of the climate system, the World Meteorological Organization and the International Oceanographic Commission have established a Global Climate Observing System (GCOS). Initially GCOS uses existing atmospheric, oceanic and terrestrial networks. Later GCOS will aim to amplify and improve the observational networks where needed and possible.

Observations alone are not sufficient to produce a coherent and global picture of the state of the climate system. So-called data assimilation systems have been developed, which combine observations and their temporal and spatial statistics with model information to provide a coherent quantitative estimate in space and time of the state of the climate system. Data assimilation also allows the estimation of properties which cannot easily be observed directly but which are linked to the observations through physical laws. Some institutions have recently reanalysed several decades of data by means of the most recent and most sophisticated version of their data assimilation system, avoiding in this way inhomogenities due to changes in their system. However inhomogeneities in these reanalyses may still exist due to changing sources of information, such as the introduction of new satellite systems.

The 20th century

Historically, human activities such as deforestation may have had a local or regional impact, but there is no reason to expect any large human influence on the global climate before the 20th century. Observations of the global climate system during the 20th century are therefore of particular importance. Chapter 2 presents evidence that there has been a mean global warming of 0.4 to 0.8°C of the atmosphere at the surface since the late 19th century. Figure 2.1 of Chapter 2 shows that this increase took place in two distinct phases, the first one between 1910 and 1945, and recently since 1976. Recent years have been exceptionally warm, with a larger increase in minimum than in maximum temperatures possibly related, among other factors, to an increase in cloud cover. Surface temperature records indicate that the 1990s are likely to have been the warmest decade of the millennium in the Northern hemisphere, and 1998 is likely to have been the warmest year. For instrumentally recorded history, 1998 has been the warmest year globally. Concomitant with this temperature increase, sea level has risen during the 20th century by 10 to 20 cm and there has been a general retreat of glaciers worldwide, except in a few maritime regions, e.g. Norway and New Zealand (Chapter 11).

Regional changes are also apparent. The observed warming has been largest over the mid- and high-latitude continents in winter and spring. Precipitation trends vary considerably geographically and, moreover, data in most of the Southern Hemisphere and over the oceans are scarce. From the data available, it appears that precipitation has increased over land in mid- and high latitudes of the Northern Hemisphere, especially during winter and early spring, and over most Southern Hemisphere land areas. Over the tropical and the Northern Hemisphere subtropical land areas, particularly over the Mediterranean region during winter, conditions have become drier. In contrast, over large parts of the tropical oceans rainfall has increased.

There is considerable variability of the atmospheric circulation at long time-scales. The NAO for example, with its strong influence on the weather and climate of extratropical Eurasia, fluctuates on multi-annual and multi-decadal time-scales, perhaps influenced by varying temperature patterns in the Atlantic Ocean. Since the 1970s the NAO has been in a phase that gives stronger westerly winds in winter. Recent ENSO behaviour seems to have been unusual compared to that of previous decades: there is evidence that El Niño episodes since the mid-1970s have been relatively more frequent than the opposite La Niña episodes.

There are suggestions that the occurrence of extreme weather events has changed in certain areas, but a global pattern is not yet apparent. For example, it is likely that in many regions of the world, both in the Northern and Southern Hemisphere, there has been a disproportionate increase in heavy and extreme precipitation rates in areas where the total precipitation has increased. Across most of the globe there has been a decrease in the frequency of much below-normal seasonal temperatures.

A detailed assessment of observed climate variability and change may be found in Chapter 2, and of observed sea level change in Chapter 11. Figure 2.39 of Chapter 2 summarises observed variations in temperature and the hydrological cycle.

Detection and attribution

The fact that the global mean temperature has increased since the late 19th century and that other trends have been observed does not necessarily mean that an anthropogenic effect on the climate system has been identified. Climate has always varied on all time-scales, so the observed change may be natural. A more detailed analysis is required to provide evidence of a human impact.

Identifying human-induced climate change requires two steps. First it must be demonstrated that an observed climate change is unusual in a statistical sense. This is the detection problem. For this to be successful one has to know quantitatively how climate varies naturally. Although estimates have improved since the SAR, there is still considerable uncertainty in the magnitude of this natural climate variability. The SAR concluded nevertheless, on the basis of careful analyses, that "the observed change in global mean, annually averaged temperature over the last century is unlikely to be due entirely to natural fluctuations of the climate system".

Having detected a climatic change, the most likely cause of that change has to be established. This is the attribution problem. Can one attribute the detected change to human activities, or could it also be due to natural causes? Also attribution is a statistical process. Neither detection nor attribution can ever be "certain", but only probable in a statistical sense. The attribution problem has been addressed by comparing the temporal and spatial patterns of the observed temperature increase with model calculations based on anthropogenic forcing by greenhouse gases and aerosols, on the assumption that these patterns carry a fingerprint of their cause. In this way the SAR found that "there is evidence of an emerging pattern of climate response to forcing by greenhouse gases and sulphate aerosols in the observed climate record". Since the SAR new results have become available which tend to support this conclusion. The present status of the detection of climate change and attribution of its causes is assessed in Chapter 12.

1.4 A 'Road-map' to this Report

This Report, the third IPCC Working Group I Assessment Report since 1990, assesses the state of scientific understanding of the climate system and its variability and change, in particular human-induced climate change. This section provides a 'road map' to the 14 chapters of this report and the major issues they are designed to address. Each chapter provides an initial summary of the Working Group I Second Assessment Report (IPCC, 1996) and then goes on to emphasise the progress made since then. The chapters can be viewed as covering the following three broad areas: *past* changes and the factors that can force climate change (Chapters 2 to 6), our *present* understanding and ability to model the climate system (Chapters 7, 8 and 14) and possible *future* climate change (Chapters 9 to 13).

In order to understand, assess and quantify the possible human influence on climate, an analysis of past climate variability and change is required (Chapter 2). The chapter tackles such questions as: how much is the world warming and is the recent global warming unusual? It looks in detail at trends and variability during the recent instrumental period (the last 100 years or so) and draws on palaeo-data to put them into the context of climate over much longer periods.

There are many factors that are known to influence climate, both natural and human-induced. The increase in concentrations of greenhouse gases and aerosols through human activity is of particular concern. Chapters 3 to 5 examine how well the three most important human contributions to the changing composition of the atmosphere; carbon dioxide, other greenhouse gases and aerosols, are understood, including the physical, chemical and biological processes which determine the atmospheric concentrations of these components. The next step, taken in Chapter 6, is to evaluate how this change in atmospheric composition has affected radiative forcing within the context of other factors such as land-use change, volcanic eruptions and solar variations.

Understanding the climate response to these various radiative forcings and projecting how they could affect future climate requires an understanding of the physical processes and feedbacks in the climate system and an ability to model them (Chapter 7). The only tools available for such projections of future climate are numerical models of the climate system of various complexity. An evaluation of such models against observations of the present and past climate and model intercomparisons provide the basis for confidence in such tools (Chapter 8).

Climate models together with scenarios of future emissions of radiatively active atmospheric components, as for example the SRES scenarios (Nakićenović *et al.*, 2000), recently developed by IPCC specifically for this purpose, are used to project future climate change. State-of-the-art projections for the next 100 years are assessed in Chapter 9, mainly at a global level, but also including large-scale patterns, their spatial and temporal variability and extreme events. Partly in response to the need for more details of climate change at a regional level, research in this area has been particularly active over the last 5 years. A new chapter, compared to previous assessments, has been included which examines the various techniques available to derive regional climate projections and, as far as is currently possible, assesses regional climate change information (Chapter 10). Chapter 11 assesses the current state of knowledge of the rate of change of global average and regional sea level in response to climate change.

A key conclusion from the SAR was that “the balance of evidence suggests that there is a discernible human influence on global climate”. Chapter 12 assesses research over the last 5 years on the detection and attribution of climate change drawing on the developments in observational research (Chapters 2 to 6) and modelling (Chapters 7 to 10) to consider how this conclusion has changed.

Data derived directly from projections with climate models are often inappropriate for assessing the impacts of climate change which can require detailed, regional or local information as well as observational data describing current (or baseline) climate. Climate change scenarios are plausible representations of future climate constructed explicitly for impact assessment and form a key link between IPCC Working Groups I and II. For the first time, Working Group I have included a chapter dedicated to climate scenarios (Chapter 13) – this is intended to provide an assessment of scenario generation techniques, rather than to present scenarios themselves.

All chapters of the report highlight areas of certainty and uncertainty, and gaps in current knowledge. Chapter 14 draws together this information to present key areas that need to be addressed to advance understanding and reduce uncertainty in the science of climate change.

A comprehensive and integrated summary of all results of this assessment report may be found in the Technical Summary in this volume. A brief summary highlighting points of particular policy relevance is presented in the Summary for Policymakers.

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