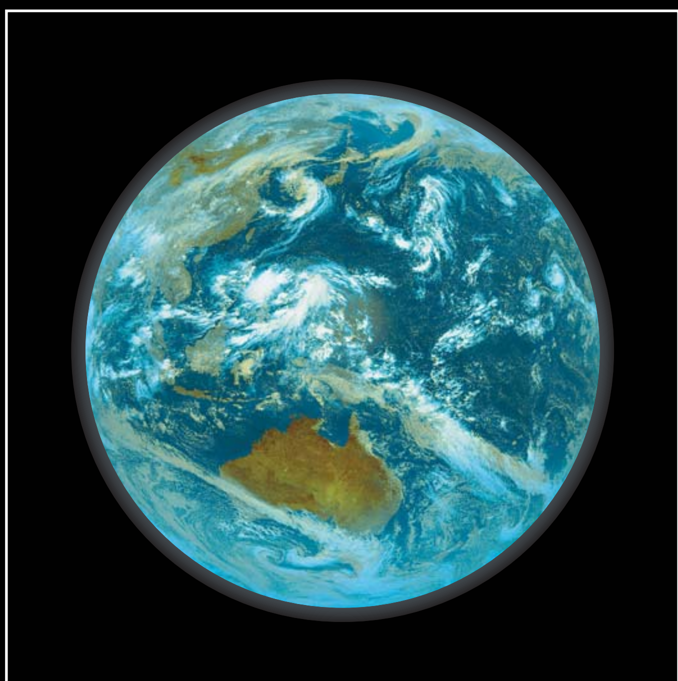
The Greenhouse Effect and Climate Change



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Introduction

The greenhouse effect is a natural process that plays a major part in shaping the earth's climate. It produces the relatively warm and hospitable environment near the earth's surface where humans and other life-forms have been able to develop and prosper. It is one of a large number of physical, chemical and biological processes that combine and interact to determine the earth's climate.

Climate, whether of the earth as a whole or of a single country or location, is often described as the synthesis of weather recorded over a long period of time. It is defined in terms of long-term averages and other statistics of weather conditions, including the frequencies of extreme events. Climate is far from static. Just as weather patterns change from day to day, the climate changes too, over a range of time frames from years, decades and centuries to millennia, and on the longer time-scales corresponding to the geological history of the earth. These naturally occurring changes, driven by factors both internal and external to the climate system, are intrinsic to climate itself.

But not all changes in climate are due to natural processes. Humans have also exerted an influence. Through building cities and altering patterns of land use, people have changed climate at the local scale. Through a range of activities since the industrial era of the mid-19th century, such as accelerated use of fossil fuels and broadscale deforestation and land use changes, humans have also contributed to an enhancement of the natural greenhouse effect. This enhanced greenhouse effect results from an increase in the atmospheric concentrations of the so-called greenhouse gases, such as carbon dioxide and methane, and is widely believed to be responsible for the observed increase in global mean temperatures through the 20th century.

The relationship between the enhanced greenhouse effect and global climate change is far from simple. Not only do increased concentrations of greenhouse gases affect the atmosphere, but also the oceans, soil and biosphere. These effects are still not completely understood. Also, complex feedback mechanisms within the climate system can act to amplify greenhouse-induced climate change, or even counteract it.

This booklet presents the scientific basis for understanding the nature of human-induced climate change within the context of the complex and naturally-varying global climate system. It describes:

- the important role of the natural greenhouse effect together with a number of other large-scale processes in determining the range of temperatures observed at the earth's surface;
- the natural and human influences that force changes in climate;
- the observed behaviour of climate in the recent and distant past;
- the basis for scientific concern at the prospect of human-induced climate change;
- how computer models of the global climate system are used to project potential changes in climate on a range of time and space scales;
- the coordinated actions being taken by the international scientific community to monitor, understand and assess potential future levels of climate change; and
- recent scientific assessments of possible human-induced climate change.

The mechanisms of climate

The major factors that determine the patterns of climate on earth can be explained in terms of:

- the strength of the incident radiation from the sun, which determines the overall planetary temperature of the earth;
- the spherical shape of the earth and the orientation of its axis;
- the greenhouse effect of water vapour and other radiatively active trace gases;
- the various physical, chemical and biological processes that take place within the atmosphere-geosphere-biosphere climate system, in particular:
  - the global energy balance,
  - the global water cycle,
  - the global carbon cycle and other biogeochemical cycles;
- the rotation of the earth, which substantially modifies the large-scale thermally-driven circulation patterns of the atmosphere and ocean; and
- the distribution of continents and oceans.

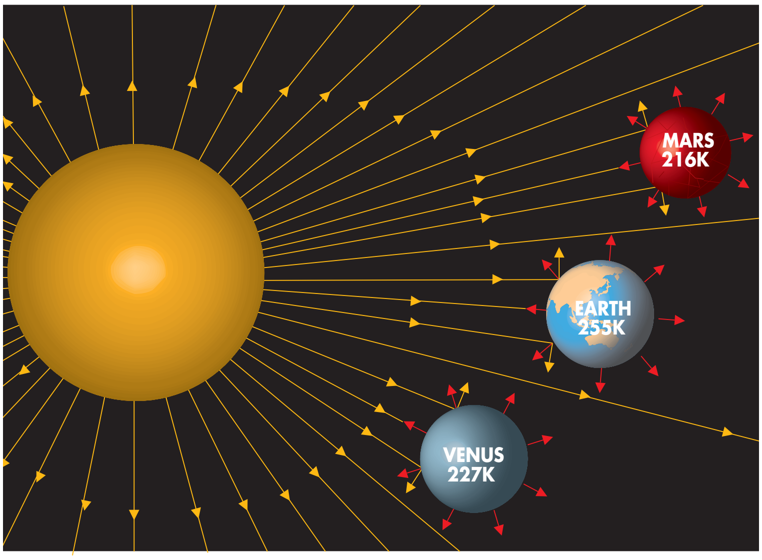


Figure 1. The geometry of the sun-earth system and the planetary radiative temperatures of Earth, Venus and Mars. A proportion of the short wave radiation from the sun (orange arrows) is reflected back to space, as determined by the albedo or reflectivity of the planet, but the absorbed short wave radiation heats the planets which in turn radiate long wave energy back to space (red arrows). Sizes and distances are not to scale.

Radiative equilibrium of the planets

The dominant influences on the overall temperature of each of the inner planets are the intensity of the sun's radiation, the planet's distance from the sun and its albedo or reflectivity for solar radiation. Given the amount of solar radiation incident on the earth (approximately 1360 W m^{-2} as an annual average) and an approximate albedo of 0.3, it is a simple matter to calculate an effective planetary temperature for the earth by noting that the infrared (long wave) radiation emitted to space by the planet is proportional to the fourth power of its absolute temperature. By equating the emitted (long wave) radiation to the absorbed (short wave) radiation, the earth's planetary temperature can be estimated, that is the average temperature in the absence of any other influences, which turns out to be -18°C (255K). The corresponding planetary temperature for the highly reflective planet Venus is -46°C (227K) while that for Mars is -57°C (216K) (Figure 1).

The shape of the earth

Because of the spherical shape of the earth, the equatorial regions, where the sun shines overhead, receive much more solar radiation per unit area than the poles, where the sun's rays strike the earth obliquely (Figure 2). If each latitude band were individually in radiative equilibrium (i.e. incoming short wave and outgoing long wave radiation were in balance), the equatorial belt would reach temperatures in excess of 100°C (373K) around solar noon and the poles would be close to absolute zero (0K or –273°C). In the real world, however, atmospheric and oceanic circulations transport heat from the equator to the poles. This substantially reduces the poleward temperature gradients from those shown in Figure 2.

The greenhouse effect

The earth is not, of course, the simple solid ball we have assumed so far. It is surrounded by a thin layer of air (Figure 3), held to it by gravity and consisting almost entirely of nitrogen (78% by volume) and oxygen (21%).

These major constituents are essentially transparent to both the incoming solar (short wave) radiation and the infrared (long wave) radiation emitted upward from the earth's surface. There is also a number of minor constituents, especially water vapour and carbon dioxide, which are largely transparent to the incoming solar radiation, but strongly absorb the infrared radiation emitted from the ground. Figure 4 illustrates the absorption spectra for the two most abundant of these radiatively active gases. The most significant is water vapour, which is not well mixed and may vary locally from less than 0.01% by volume to more than three per cent. The next most abundant is carbon dioxide (CO_2) which has a long lifetime in the atmosphere and is well mixed around the globe. Other important trace gases are methane, nitrous oxide, ozone and anthropogenic halocarbon compounds, such as the ozone-depleting chlorofluorocarbons and hydrofluorocarbons.

The radiation absorbed by these gases is re-emitted in all directions, some back toward the surface leading to a net warming of the surface. Through what is widely, but inaccurately, referred to as the greenhouse effect, these so-called greenhouse gases trap heat in the near surface layers of the atmosphere and thus cause the earth's surface to be considerably warmer than if there were no greenhouse effect.

The mechanism of the natural greenhouse effect and its impact on the earth's surface and atmospheric temperatures is shown schematically in Figure 5. In the left panel, for the hypothetical situation of no greenhouse gases, the ground heats up until it reaches the temperature at which the outward radiation to space equals the incoming solar radiation, i.e., the planetary radiative temperature, T_O, of -18°C (255K) noted earlier. In the more realistic situation in the middle panel, the greenhouse gases in the atmosphere absorb some of the outgoing terrestrial (infrared) radiation and re-radiate infrared energy in all directions. There is thus now more radiant energy (short wave plus long wave) being absorbed by the ground and so it heats up further, by some tens of degrees, until the upward infrared emission just balances the total downward infrared and solar radiation at a surface temperature of T_S. With a normal distribution of greenhouse gases in the atmosphere, and notwithstanding the many other physical processes that come into play, this leads to a vertical temperature profile in the atmosphere and ocean taking the general form of the solid curve in the right panel of the diagram. The difference (T_S-T_O) is a measure of the greenhouse effect at the earth's surface.

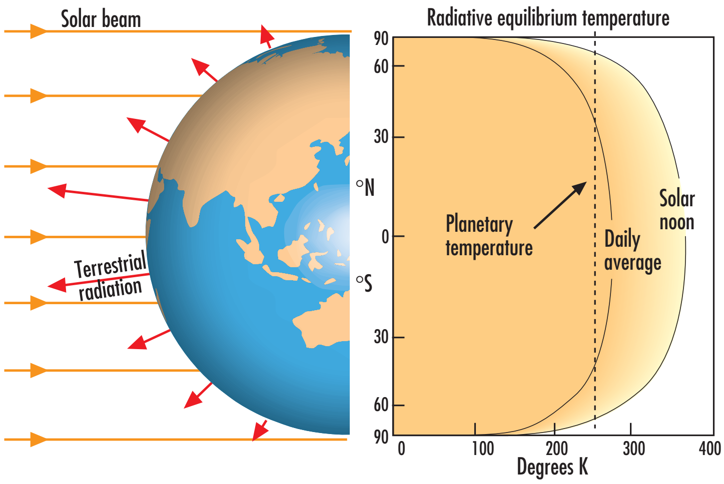


Figure 2. A schematic representation of the hypothetical situation of latitude-by-latitude balance between the incoming short wave and outgoing long wave radiation and the resulting north-south radiative equilibrium temperature profiles that would result, at solar noon and as a daily average around the earth, compared with the overall planetary radiative equilibrium temperature of 255K.

Figure 3. A slice through the earth's atmosphere viewed from space.

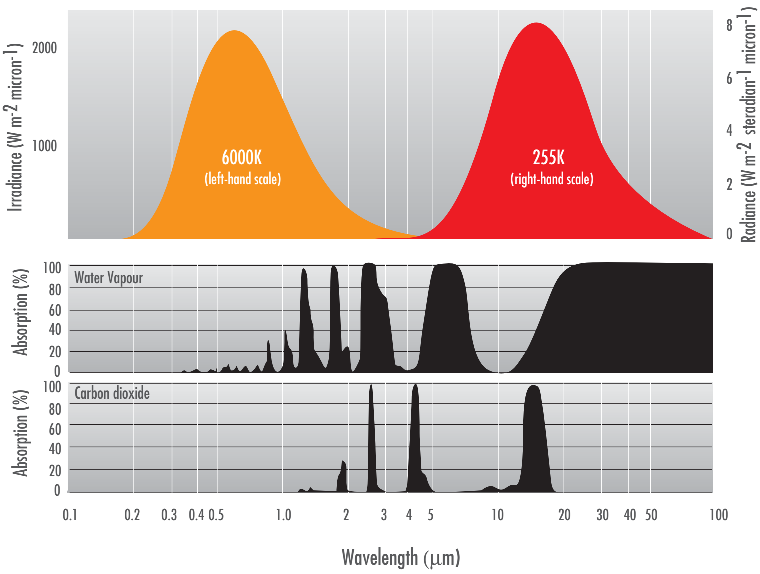


Figure 4. The radiation absorption characteristics of water vapour and carbon dioxide as a function of wavelength. The upper portion of the chart shows the wavelength distribution of radiation emitted from black bodies radiating at 6000K (approximately the solar photosphere) and 255K (approximately the earth's planetary temperature), with the solar irradiance measured at the mean distance of the earth from the sun. The percentage absorption of a vertical beam by representative atmospheric concentrations of water vapour (H_2O) and carbon dioxide (CO_2) are shown in the lower panels.

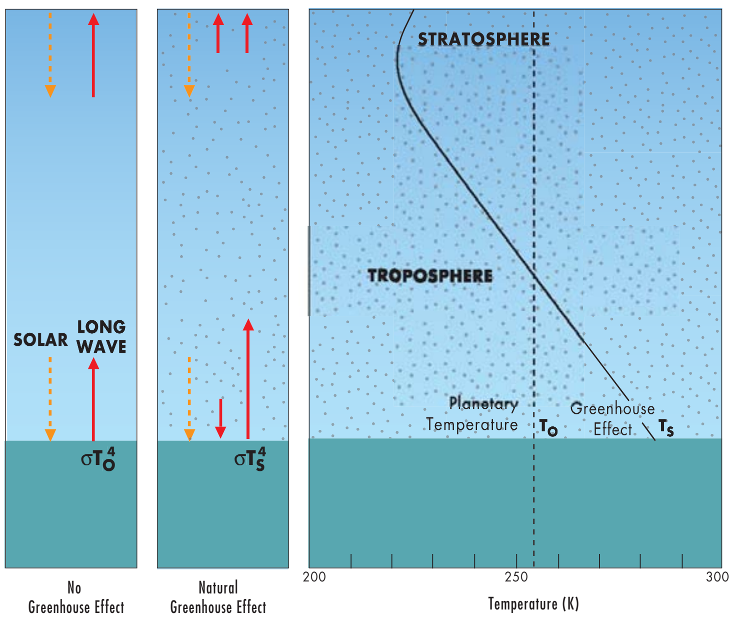


Figure 5. The natural greenhouse effect (T_S-T_O) depicted as the difference between the radiative equilibrium surface temperature of the atmosphere of pre-industrial times (centre panel) and that of a hypothetical atmosphere with no radiatively active gases but the same albedo as at present (left panel). The right panel of the diagram shows schematically the radiative equilibrium temperature profile in the atmosphere resulting from the greenhouse effect compared with the planetary temperature of 255K.

An illustration of the importance of the greenhouse effect comes from a study of our neighbouring planets, most particularly Venus (Table 1). Venus is closer to the Sun than Earth but much more reflective. As shown in Figure 1, its planetary temperature, calculated solely on the basis of its distance from the Sun and its albedo, is -46°C (227K), some 28°C cooler than the Earth. However, the surface of Venus has been measured directly by space probes, and mean surface temperatures of the order of 464°C (737K) have been reported. This temperature is consistent with what greenhouse theory tells us for a planet with Venus's extremely dense and carbon dioxide rich atmosphere. While Venus is twice as far from the Sun as Mercury, its surface temperature is considerably warmer because Mercury has no atmosphere and thus no greenhouse effect. The high carbon dioxide content of the Martian atmosphere is offset by its thinness, resulting in a negligible greenhouse effect and a large range in surface temperatures, from equator to pole and from day to night.

The climate system

The processes that determine the detailed horizontal and vertical patterns of temperature in the real atmosphere are much more complex than the simple radiative equilibrium models represented in Figures 1, 2 and 5. A range of other vertical and horizontal heat exchange processes are called into play in the atmosphere. The oceans also play a major part. The detailed patterns of climate on earth are produced by a complex web of interacting physical, chemical and biological processes within the global climate system (Figure 6). Particularly important roles are played by the global heat, water and carbon cycles. The complex interactions between the individual components of the climate system mean that any change in one component will affect the other components in some way.

Global energy balance

The global energy balance at the top of the atmosphere and at the earth's surface are sum-

Table 1. The greenhouse effect on planets of the inner solar system.

Planet	Mean distance from Sun (10^6 km)	Percentage volume of main greenhouse gases in atmosphere	Average albedo	Surface temperature in absence of greenhouse effect	Observed mean surface temperature	Greenhouse effect
Mercury	58	no atmosphere	0.06	167°C	167°C	0°C
Venus	108	> 90% CO_2 but extremely dense (surface pressure100 times that of Earth)	0.78	-46°C	464°C	510°C
Earth	150	approx 0.03% CO_2; approx 1% H_2O	0.30	-18°C	15°C	33°C
Mars	228	> 90% CO_2 but very thin (surface pressure 0.01 that of Earth)	0.17	-57°C	Approx -53°C	4°C

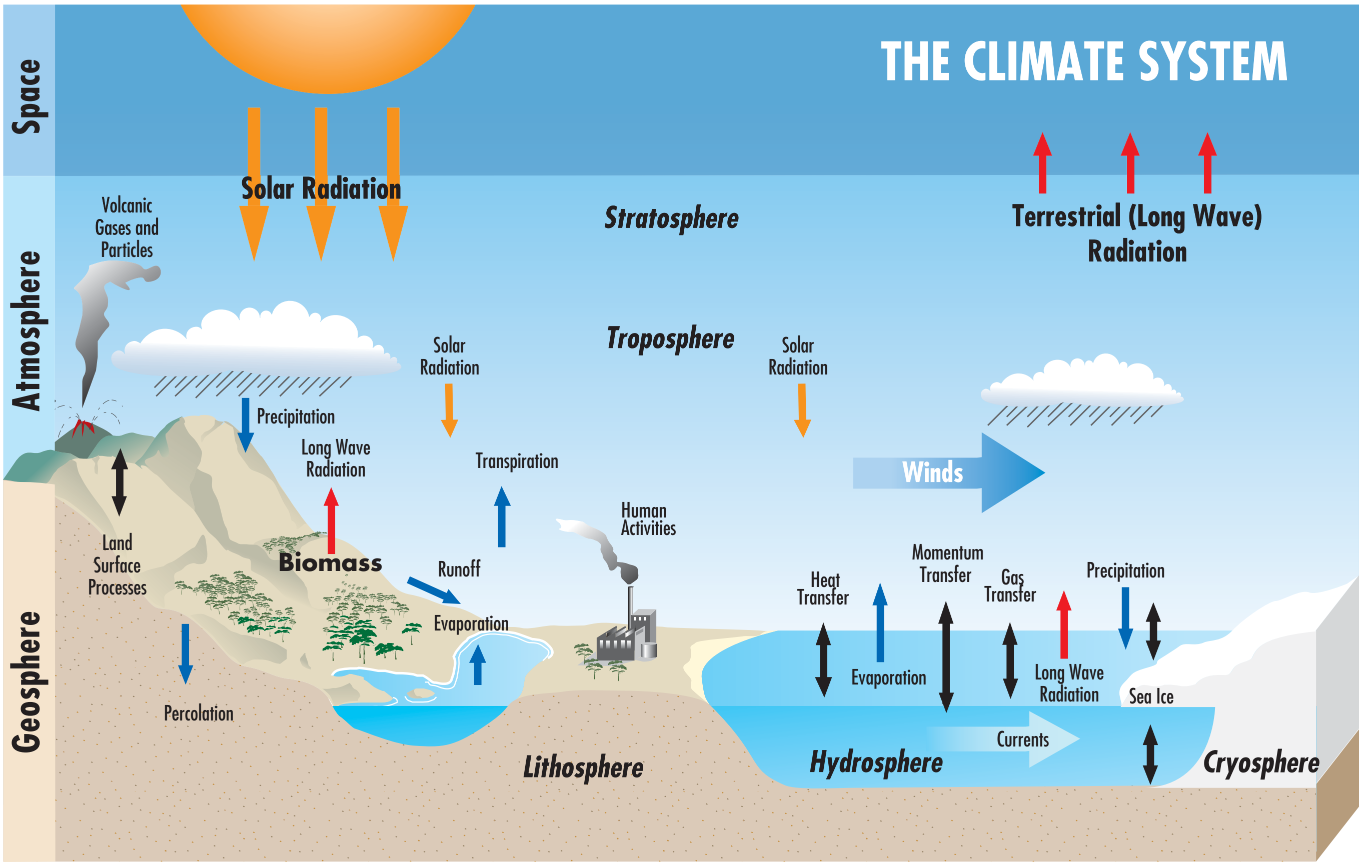


Figure 6. The components of the global climate system consisting of the atmosphere (including the troposphere and stratosphere), the geosphere (which includes the solid earth (lithosphere), the oceans, rivers and inland water masses (hydrosphere) and the snow, ice and permafrost (cryosphere)) and the biosphere (the transition zone between them within which most plant and animal life exists and most living and dead organic matter (biomass) is to be found). The figure also shows the main physical processes that take place within the climate system and thus exert an influence on climate.

marised in Figure 7. In addition to the greenhouse effect, a number of other processes heat and cool the atmosphere. These include the turbulent transfer of sensible and latent heat from the sun-warmed land and water surfaces to the lower layers of the atmosphere. This produces convective and condensation heating of the lower and middle troposphere and a rather different vertical temperature profile from that shown for the greenhouse effect alone in Figure 5.

Global water cycle

The hydrological cycle is central to the mechanisms of climate. Its simplest, globally averaged form is shown schematically in Figure 8. Notice the vital role of the transport of atmospheric moisture from the oceans, which cover more than two-thirds of the globe, to the continents to balance the discharge from rivers and groundwater to the oceans. Water vapour is the most important of the greenhouse gases, in terms of its influence on climate (see Climate model feedbacks, p. 40), and the water and energy cycles of the atmosphere are closely interlinked.

Global carbon cycle

The cycling of carbon dioxide, the second most significant greenhouse gas in the atmosphere, within the climate system is shown schematically in Figure 9. In reality, the global carbon cycle is far more complex. The important thing to note is the large natural cycling rate between the atmosphere and the marine and terrestrial biosphere. During the 1990s, fossil fuel burning (together with, to a lesser extent, cement production) released an extra 5.4 gigatonnes (1 gigatonne equals 10^{12} kg) of carbon into the atmosphere each year. Land-use changes cause both release and uptake of carbon dioxide. Tropical deforestation is estimated to result in an average emission to the atmosphere while forest regrowth in northern hemisphere mid and high latitudes is estimated to contribute a carbon sink. There are also terrestrial carbon sinks associated with enhanced plant growth (CO_2 fertilisation) and anthropogenic nitrogen fertilisation. Overall there is believed to have been a net flow of carbon from the atmosphere to the land and terrestrial biosphere of around 1.4 GtC/year in recent years.

Some additional atmospheric carbon eventually passes into the deep ocean, with the oceans calculated to have absorbed a net 1.9 GtC/year during the 1990s. Allowing for carbon sinks, the net increase in atmospheric carbon has been calculated at 3.2±0.1 GtC/year during the 1990s. This ranged from 1.9 to 6.0 GtC/year for individual years.

Atmospheric circulation

A key influence on the climate system, not captured in the globally averaged representations of Figures 6-9, is the dynamic effect of the rotation of the earth. The radiatively-induced temperature gradient between the equator and the poles (Figure 2), coupled with the radiative-convective redistribution of this heat into the tropical troposphere, forces a meridional overturning in the atmosphere, with the heated air rising in the tropics and moving poleward. The poleward-moving air aloft attempts to conserve the absolute angular momentum it acquired at the surface near the equator, and consequently it accelerates rapidly eastward relative to the earth's surface, as shown in Figure 10.

The very strong westerly winds in the upper atmosphere that would result from the meridional circulation shown in Figure 10 are unstable and break down in the middle latitudes into a series of waves and eddies which overlie the familiar patterns of eastward moving surface 'highs' and 'lows' (Figure 11). As a result, the single meridional circulation cell that would otherwise be expected in each hemisphere (i.e. Figure 10) is replaced by three separate cells (a tropical or Hadley cell, a mid-latitude Ferrel cell and a polar cell) with the regions of strongest ascent and rainfall in the inner tropics and near 60° latitude and the strongest descent between the Hadley and Ferrel cells corresponding to the mid-latitude high pressure belts.

Figure 7. The global radiation balance at the top of the atmosphere and at the earth's surface. Part of the total incoming solar energy 340 W m^{-2} is absorbed by clouds and atmospheric gases and part is reflected by clouds, atmospheric gases and the ground (land and water surfaces). Approximately half (170 W m^{-2}) is absorbed by the ground. Some of this energy is re-radiated upward and some transferred to the atmosphere as 'sensible' and 'latent' heat by turbulence and convection. The atmosphere radiates infrared radiation in all directions. When balance is achieved in the atmosphere, the total (short wave and long wave) upward radiation from the top of the atmosphere equals the 340 W m^{-2} received from the sun.

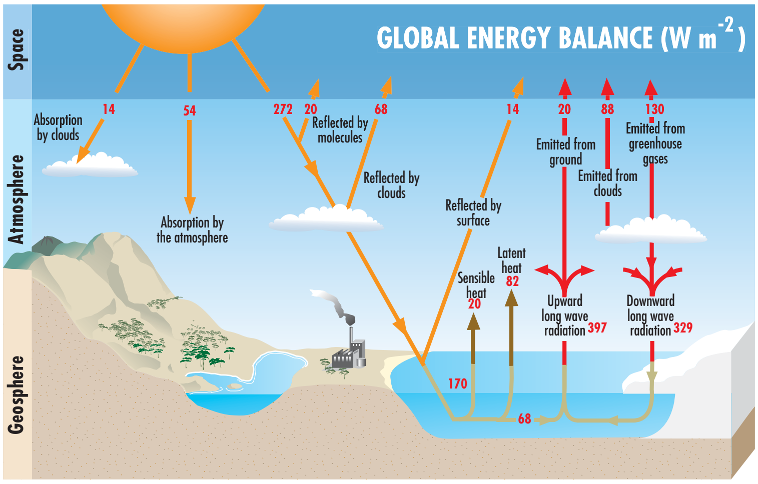


Figure 8. The global water cycle. This schematic representation shows the evaporation of water from the oceans and land surface, its transport within the atmosphere, its condensation to form clouds and its return to earth as precipitation (rain and snow) both over the oceans and over land where it may either run off to the ocean in rivers or percolate into the ground and eventually reach the ocean as groundwater flow. The fluxes are shown in units of 10^{12} m^3/year and the storages in units of 10^{12} m^3.

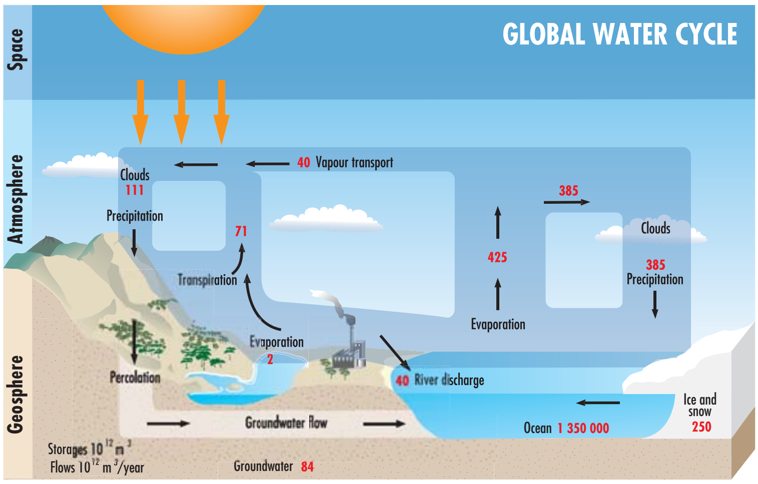
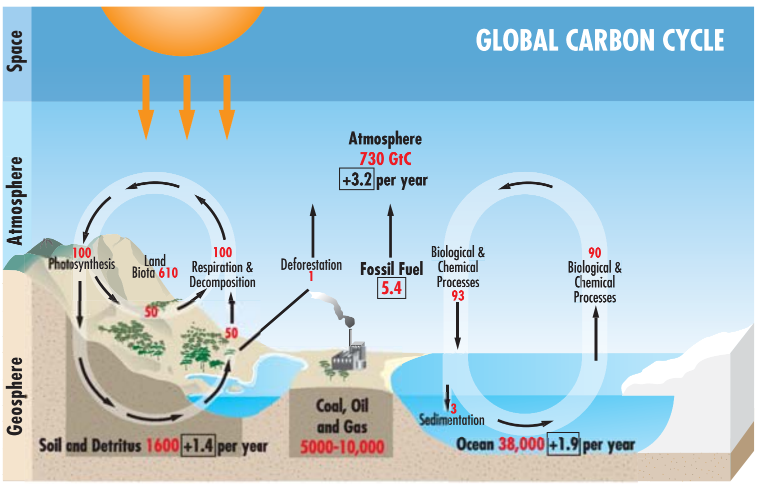


Figure 9. The global carbon cycle. This schematic representation shows the global carbon reservoirs in gigatonnes of carbon (1GtC = 10^{12} kg) and the annual fluxes and accumulation rates in GtC/year, calculated over the period 1990 to 1999. The values shown are approximate and considerable uncertainties exist as to some of the flow values.



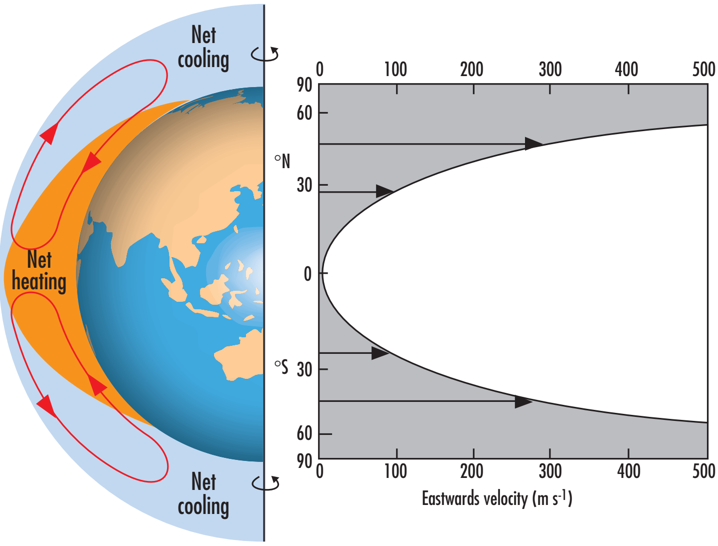


Figure 10. The origin of the atmospheric circulation. The strong net heating of the lower tropical atmosphere by sensible and latent heat flux from the solar-heated surface drives the north-south overturning shown schematically on the left. The poleward moving air in the upper atmosphere attempts to conserve the absolute angular momentum it acquired through frictional drag at the surface near the equator and accelerates rapidly eastward relative to the earth's surface as shown on the right.

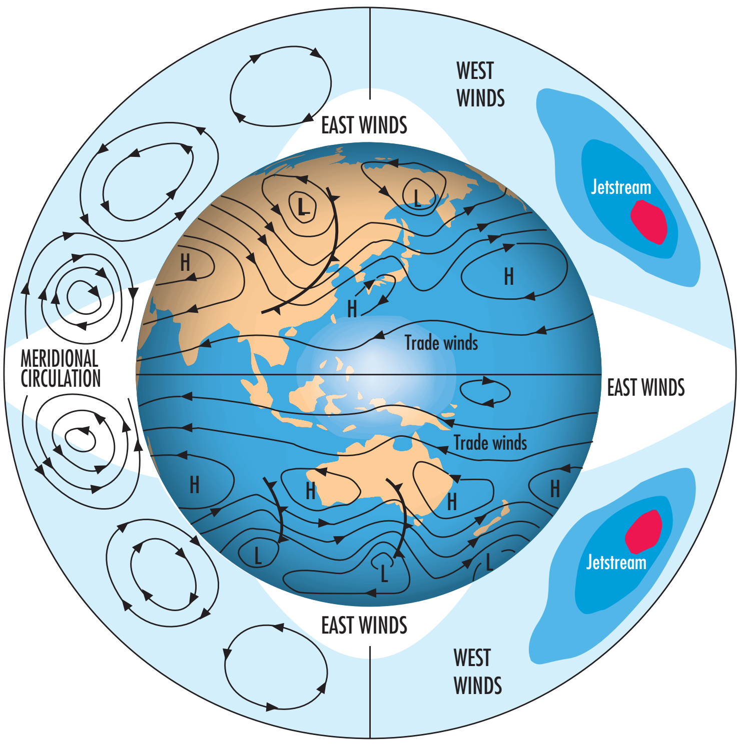


Figure 11. The essential features of the general circulation of the atmosphere showing a typical daily pattern of surface pressure systems and (in greatly exaggerated vertical scale) the zonally averaged meridional (left) and zonal circulation (right).

The role of oceans

The interaction between the thermally driven (and essentially zonally symmetric) circulation we have considered so far and the distribution of continents and oceans leads to substantial variation of climatic patterns in the east-west direction over the globe. One particularly significant influence is the east-west Walker Circulation of the tropical Pacific (Figure 12).

Ocean covers 71% of the earth's surface to an average depth of 3800 m and plays a key role in redistributing heat around the globe. The relative heat capacity of the ocean compared to the atmosphere is huge - the heat capacity of the entire atmosphere is equivalent to that of only 3.2 m of ocean depth. Convection and wind-induced mechanical mixing within the ocean result in an active mixed layer which averages about 50 m in depth, varying with season and region.

Typically, values range from less than 50 m during spring and early summer (the heating season) to over 100 m in autumn and winter when surface cooling helps trigger convection. Consequently, considerable amounts of thermal energy are stored in the ocean. The ocean is, however, not in equilibrium with the atmospheric and external climate system influences because of the long time-scales involved in many oceanic processes, such as the large-scale overturning of the deep ocean which takes thousands of years. Water carried from the surface to the deep ocean is isolated from atmospheric influence and hence may sequester heat for periods of a thousand years or more.

In some respects, processes in the ocean are simpler than in the atmosphere, since they do not involve clouds and condensation. While the atmosphere is forced thermally throughout its volume, the ocean receives almost all its thermal and mechanical forcing at the surface. However, because the ocean is constrained by complex ocean basins, there are important consequences for the flow patterns. Horizontal basin-scale circulation features, called gyres, are formed, driven predominantly by the surface winds and featuring narrow, rapidly flowing boundary currents on the western sides of the basins with slow broad return

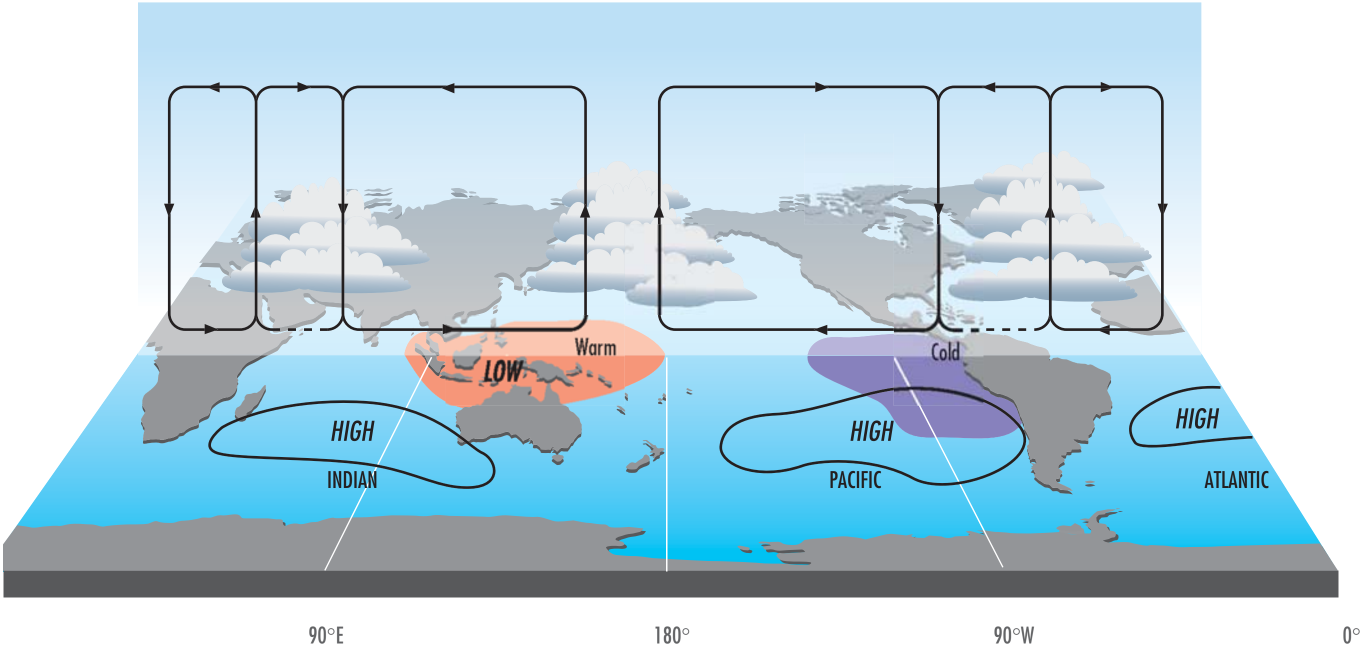


Figure 12. A schematic representation of the east-west Walker Circulation of the tropics. In normal seasons air rises over the warm western Pacific and flows eastward in the upper troposphere to subside in the eastern Pacific high pressure system and then flows westward (i.e. from high to low pressure) in the surface layers across the tropical Pacific. Weaker cells also exist over the Indian and Atlantic Oceans. In El Niño years, this circulation is weakened, the central and eastern Pacific Ocean warms and the main area of ascent moves to the central Pacific.

currents over the remainder. Examples include the East Australian Current off eastern Australia and the Gulf Stream off the east coast of North America.

There is a vigorous exchange of heat and moisture between the ocean and the atmosphere. This results in net losses of fresh water, by evaporation exceeding precipitation, in some regions (mostly the subtropics) and gains in other regions, especially at high latitudes. Consequently the density of ocean water is not constant but varies because of temperature effects and changes in salinity. This gives rise to large-scale overturning and 'thermohaline' or density-driven circulation. In simple terms, this involves the sinking of cool saline water at high latitudes and rising waters in tropical and subtropical latitudes, linked globally by the so-called 'ocean conveyor belt' (Figure 13).

Another important role of the ocean, particularly in the context of climate change, is its ability to store carbon dioxide and other greenhouse gases and to exchange them with the atmosphere.

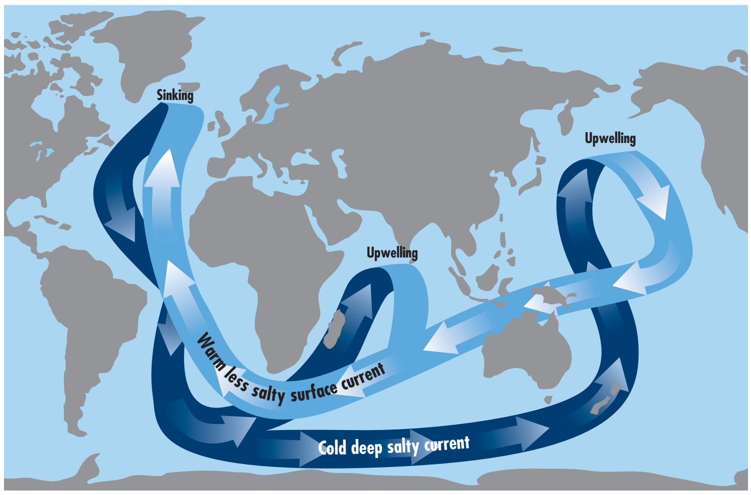


Figure 13. A simplified version of the large-scale circulation of the oceans. Water circulates globally through the oceans as though carried by a huge conveyor belt. Northward moving warm water in the North Atlantic cools and sinks to the deep ocean to resurface and be rewarmed in the Southern, Indian and North Pacific Oceans. Surface currents carry the warmer water back through the Pacific, Indian and South Atlantic and into the North Atlantic. The circuit takes almost 1000 years.

Poleward heat transport

A consequence of the differential heating between the low and high latitudes, as illustrated in Figure 10, is the surplus of incoming absorbed solar radiation over outgoing long wave radiation in low latitudes, with a deficit at high latitudes. This is demonstrated, on an annual mean basis, in the upper part of Figure 14. Thus, radiative processes are continually acting to cool the high latitudes and warm the low latitudes, and it is only the poleward heat transport by the meridional circulation in the atmosphere and ocean (lower part of Figure 14) that serves to offset this. The ocean transport component is calculated as a residual after using satellite data to determine the radiatively required poleward heat transport at the top of the atmosphere and estimates of the atmospheric transports.

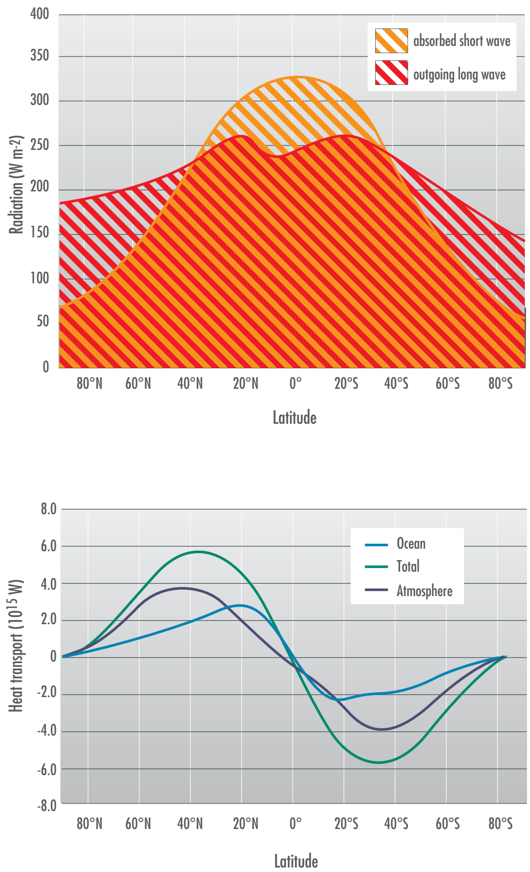


Figure 14. The pole-equator-pole radiation balance (top) and the poleward energy transport for the atmosphere and ocean (bottom) necessary to achieve radiative balance. The zonal mean absorbed short wave and outgoing long wave radiation, as measured at the top of the atmosphere, are shown with their difference highlighted to show the excess in the tropics and the deficit at high latitudes. The lower part shows the required northward heat transport for balance (green), the estimated atmospheric transports (purple) and the ocean transports (blue) computed as a residual.

Natural variability in the climate system

In addition to the annual (seasonal) cycle of climate, global and regional climates are in a perpetual state of change on time-scales from months to millions of years. As a result, society and nature are in a continuous process of adaptation to change. A range of factors can lead to changes in climate on these time-scales, some internal to the climate system and some external, some naturally occurring and some deriving from human activities. In addition to physical mechanisms of climate variability, there are also random, chaotic fluctuations within the climate system. These account for a significant part of the observed natural variability.

The annual cycle

On the annual time-scale, there is a significant strengthening and weakening of the incident radiation at the outer limit of the atmosphere as the earth moves between perihelion (nearest point to the sun) and aphelion (furthest from the sun) (Figure 15). However, the annual climate cycle is largely determined by the fact that the tilt of the earth's axis remains fixed as it circles the sun. When the South Pole is slanted toward the sun, the southern hemisphere receives its maximum solar irradiance for the year, and it is summer in this hemisphere. Six months later, when this pole slants away from the sun, summer is experienced in the northern hemisphere. (There is actually a lag of a few weeks between the annual cycles of solar irradiance and temperature at most locations due to heat uptake and release by the oceans, which are slower to respond to changes in solar heating than land masses.)

In mid and high latitudes, the annual cycle of solar irradiance results in relatively large variations in weather throughout the year, allowing the distinct seasons of summer, autumn, winter and spring to be defined. At any location, the annual cycle interacts with other climate forcing mechanisms to help create a range of conditions observed for any particular month or season (Figure 16). In some locations, the range of conditions experienced during a month or season may be so great that the monthly or seasonal mean may not be all that meaningful.

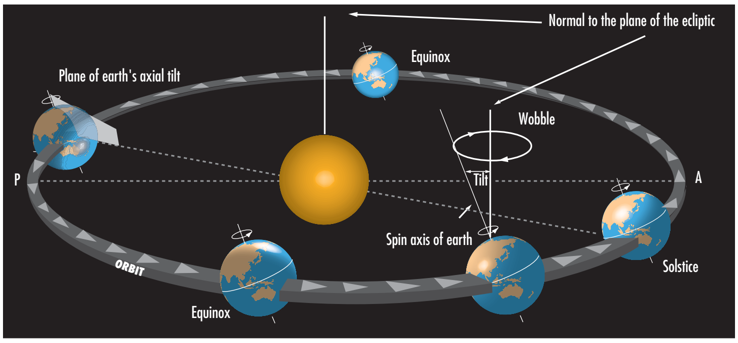


Figure 15. Geometry of the sun-earth system. The earth's orbit, the large ellipse with major axis AP and the sun at one focus, defines the plane of the ecliptic. The plane of the earth's axial tilt (shaded) is shown passing through the sun corresponding to the time of the southern summer solstice. The earth moves around its orbit in the direction of the solid arrow (period one year) while spinning about its axis in the direction shown by the thin curved arrows (period one day). The earth's spin axis describes a slow retrograde motion, called precession, shown by the thicker curved arrows (period about 22,000 years), and varies in degree of tilt from 21.5° to 24.5° (period 41,000 years).

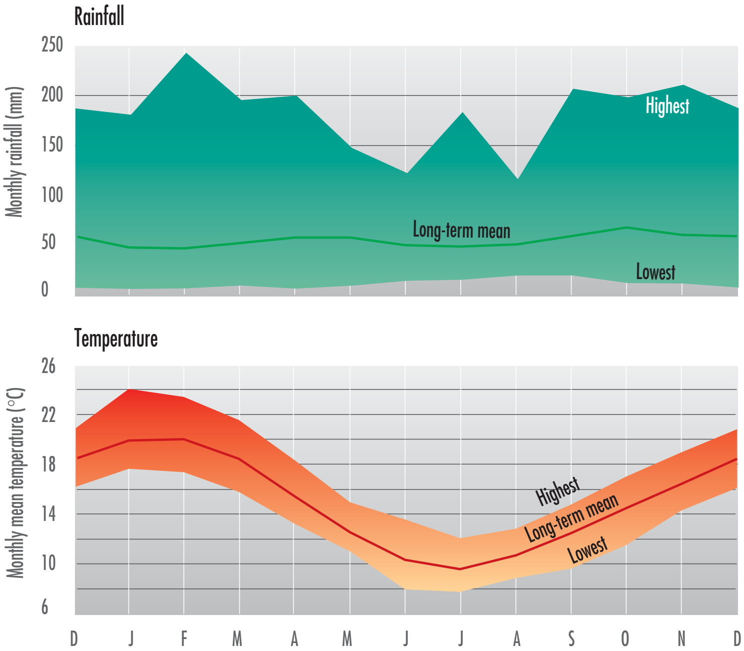


Figure 16. The annual cycle of rainfall (mm) and temperature (°C) for Melbourne, based on all years of record. In addition to the long-term monthly averages, the highest and lowest individual monthly values are also shown.

In tropical regions where the variation in solar irradiance is not as great, it is more common to define the seasonal cycle in terms of wet and dry seasons. While there is less tropical variation, it is enough to produce a recognisable pattern of movement in the region of maximum convective activity.

Orbital cycles

Even without any change in the energy output of the sun itself, there are well documented systematic variations in the orbital parameters of the earth which significantly modulate the strength and distribution of the solar energy incident on the earth. There are three major types of fluctuation in the earth's orbit - precession of the equinoxes with a cycle of 22,000 years; an obliquity cycle of 41,000 years; and a 100,000 year cycle in the eccentricity of the earth's orbit. These were used by Milutin Milankovitch in 1938 to calculate the resulting fluctuations in the solar radiation reaching the earth's surface. This has been shown to correlate well with the climatic record of the geological past. It is widely held that the onset and retreat of the great ice ages of the past million years (Figure 17) are associated with changes in the natural greenhouse effect as a result of the Milankovitch cycles.

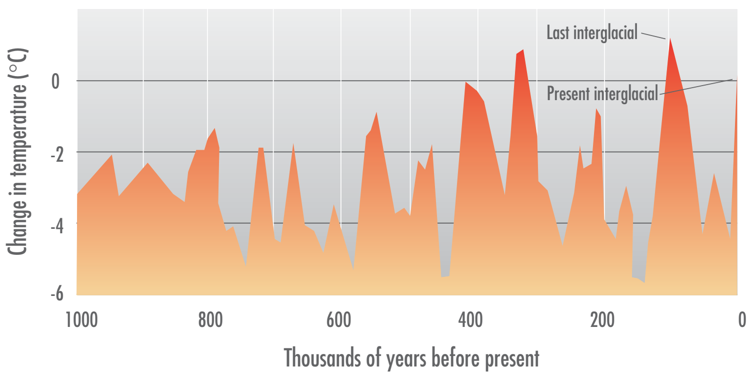


Figure 17. The succession of ice ages and interglacials of the past million years shown in terms of estimated global mean temperature anomaly (°C).

Fluctuations in solar output

The intensity of radiant energy output from the sun is known to vary over time. Fluctuations associated with the 11-year sunspot cycle are considered by some to be of special significance for climate variability. Although changes in emitted energy are quite small (of order 0.1%-0.4%), they have frequently been seen as a possible explanation for significant shifts in the earth's climate. It is often noted that the coldest part of the so called 'Little Ice Age' of the 13th to mid 19th centuries coincided with the seventeenth century 'Maunder' minimum in sunspot numbers.

There have been attempts to explain the global temperature trends of the past century in terms of sunspot-based measures of solar activity. Some correlation is evident between average sunspot numbers and temperature trends (Figure 18) and correlation has been identified between the length of the sunspot cycle and northern hemisphere mean temperature anomalies. At this stage, in the absence of identified causal linkages, this finding has not generally been accepted by the scientific community as having any real significance as the 'explanation' for the pattern of temperature changes over the last century.

Although this is an area where much more has yet to be learned, the direct solar forcing of climate by variations in solar radiation, and the indirect solar forcing via solar-related changes in atmospheric ozone, need to be considered in determining the future variations of global climate.

Fluctuations in earth's rotation rate

Because of its effects on the dynamics of the poleward-moving air driven by the equatorial heating (Figure 10), the rotation rate of the earth is critical in determining the latitudes of ascent and descent in the mean meridional circulation. Major deserts occur under regions of descent, with major rainbelts under the areas of ascent. Although small fluctuations occur over a range of time-scales, there is no evidence of recent changes in the earth's rotation rate of a magnitude that would lead to significant changes in climate.

Volcanic eruptions

Major volcanic eruptions can inject significant quantities of sulphates and other aerosols into the stratosphere, reducing the solar radiation reaching the earth's surface and leading to a transitory mean surface cooling of up to 0.5°C for several years or more. This cooling, in turn, can inject an anomaly into the internal workings of the climate system which can have impacts for decades or longer. It is believed that a significant part of the fluctuations in global mean temperature over the past century has been due to the effects of volcanic eruptions. Figure 19 shows the global temperature record corrected for the effects of El Niño events. This suggests a significant cooling impact from both the Mt Agung and El Chichon eruptions.

On 15 June 1991, the largest volcanic eruption of the 20th century, that of Mt Pinatubo, occurred in the Philippines. It is estimated that between 15 and 20 million tons of sulphur were injected into the stratosphere. This spread rapidly around the tropics producing a veil of haze and spectacular sunrises and sunsets which persisted for more than two years after the event. It is believed that the relatively cool surface and lower troposphere temperatures observed in 1992 and 1993 were due to the Mt Pinatubo eruption. Warmer temperatures reappeared in 1994 following the dispersal of the stratospheric aerosols from the eruption.

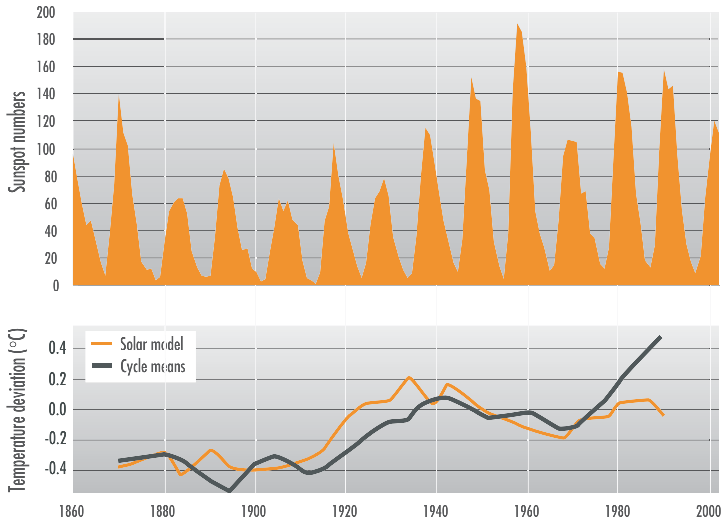


Figure 18. The sunspot cycle shown in terms of mean annual sunspot numbers (top) 1860 to 2000, and the relationship between the length of the sunspot cycle and land-only northern hemisphere mean temperature anomalies (bottom).

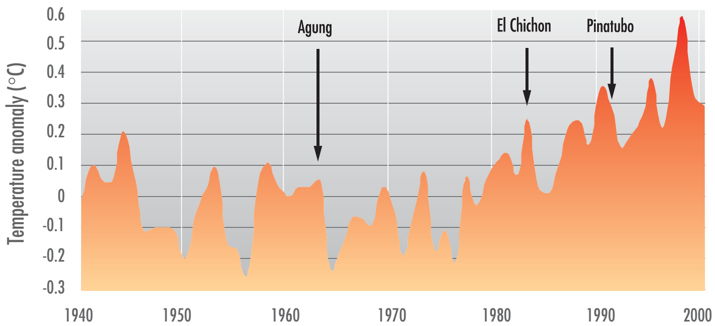


Figure 19. Recent calculations of the reduction in global mean temperature following major volcanic eruptions.

Changes in land and ocean floor topography

Changes in land and ocean floor topography, resulting from geological processes, can affect climate by influencing both the patterns of absorption of incoming solar radiation and by physically impeding the atmospheric and oceanic circulation. Such changes have been a major influence on the patterns of global climate on geological time-scales.

Internal oscillations of the climate system

Even in the absence of any external influences, the climate system fluctuates naturally on time-scales from months to thousands of years. There are several well-known natural fluctuations that have been identified through statistical analyses of observational data. These include the El Niño – Southern Oscillation, the Pacific Decadal Oscillation and the North Atlantic Oscillation.

El Niño – Southern Oscillation

One of the best-known internal fluctuations of the climate system is that associated with the El Niño phenomenon. It occurs on time-scales of 3 to 8 years and involves a well-defined life cycle of warming and cooling in the central tropical Pacific Ocean with associated shifts in surface pressure patterns (the Southern Oscillation) and in the tropical Walker Circulation (Figure 12). During an El Niño event, changes tend to occur in several climate variables, such as precipitation (Figure 20). An El Niño event generally leads to descending air and drought over eastern Australia. An important measure of the state of the El Niño-Southern Oscillation phenomena (ENSO) is the Southern Oscillation Index (SOI) - essentially a measure of the difference between the surface pressure anomalies at Tahiti and Darwin and hence, of the driving forces of the Walker Circulation. The SOI is well correlated with rainfall over parts of Australia (Figure 21) although it clearly does not explain all of the variation in rainfall. The other extreme of the cycle when the central Pacific Ocean is cooler than normal is called La Niña. Its impacts are roughly opposite to those of El Niño.

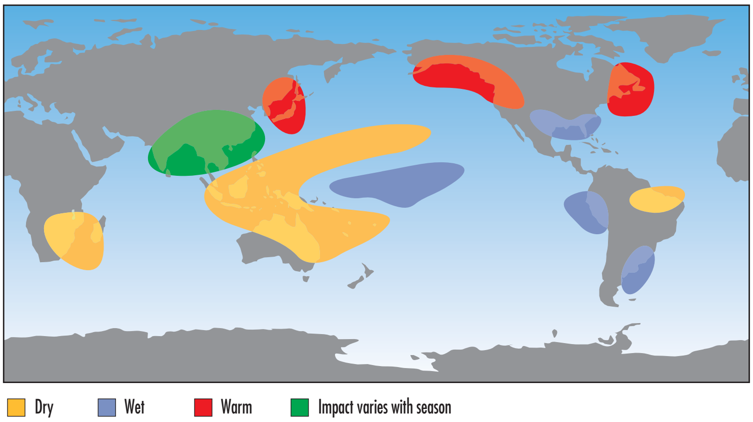


Figure 20. The patterns of climate impacts around the world during an El Niño event.

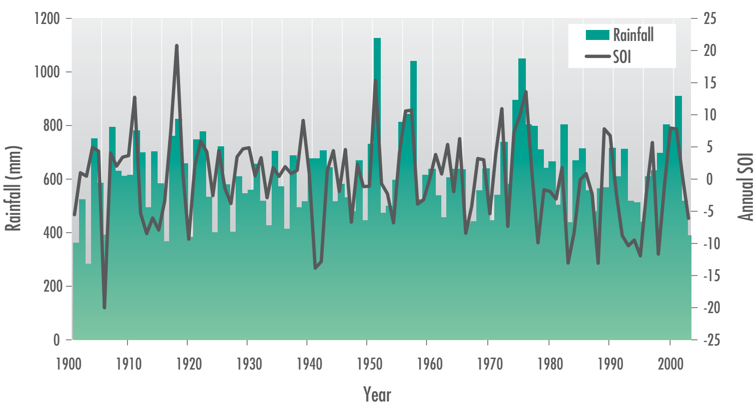


Figure 21. The relationship between the Southern Oscillation Index and the average annual rainfall over Queensland.

Pacific decadal oscillation

The Pacific Decadal Oscillation (PDO) is similar to the El Niño - La Niña cycle in that it can be detected as an irregular oscillation in sea-surface temperatures of the tropical Pacific Ocean. However, unlike El Niño, which affects climate at the annual time-scale, the PDO has a decadal cycle and influences the climate over several decades. A number of distinct phases of the PDO have been identified from the instrumental record. The PDO was in a negative phase from about 1946 to 1977 and a positive phase from 1978. It is apparent that the statistical relationships between climate and El Niño differ between phases of the PDO. For example, during the positive phase of the PDO, the relationships between El Niño and Australian precipitation and temperature are weaker than for the negative phase.

North Atlantic oscillation

The North Atlantic Oscillation (NAO) is a major climate fluctuation in the North Atlantic Ocean, involving a large-scale atmospheric oscillation between the subtropical high-pressure belt and the belt of polar lows in the northern hemisphere. The NAO tends to remain in one phase for several years before changing to the other, each phase having different impacts on weather and climate in the North Atlantic and surrounding continents.

Ocean and polar ice variations

On much longer time-scales, it appears that one major source of fluctuations of climate might be unsteadiness in the oceanic conveyor belt (Figure 13). There is substantial evidence to suggest that the Younger Dryas cooling which delayed the start of the present interglacial period (Figure 22) was associated with a temporary shut-down of the oceanic conveyor belt. It is also believed that long time-scale variations in the amount of ice locked up in the polar ice caps also have repercussions for the global climate.

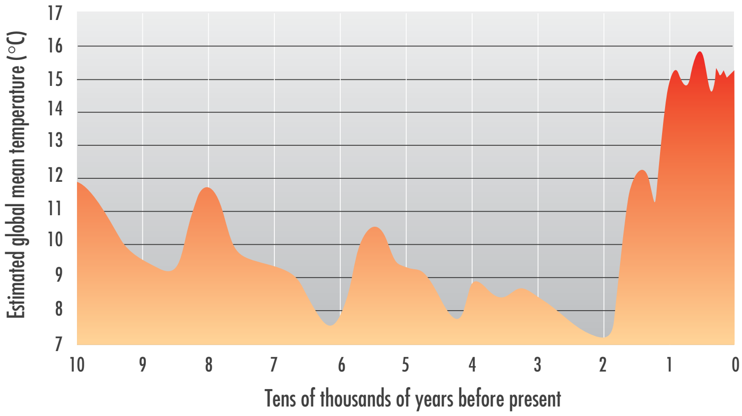


Figure 22. Estimated global mean temperatures over the past 100,000 years spanning the last ice age and the present interglacial. Note particularly the Younger Dryas cold period about 12,000 years before present which temporarily delayed the end of the last ice age.

Changing patterns of land use

Broadscale changes in land-use patterns, such as deforestation, can significantly alter the roughness and reflectivity of the surface for solar radiation, and hence the absorbed radiation, evaporation and evapotranspiration. In the process, changes in regional climate can occur. Broadscale changes in land use also impact on the global climate by enhancing the natural greenhouse effect, for example by reducing the land's capacity to absorb carbon dioxide (e.g. through deforestation) and by increasing the carbon emission from the land (e.g. through increased biomass decay), both of which lead to greater concentrations of greenhouse gases.

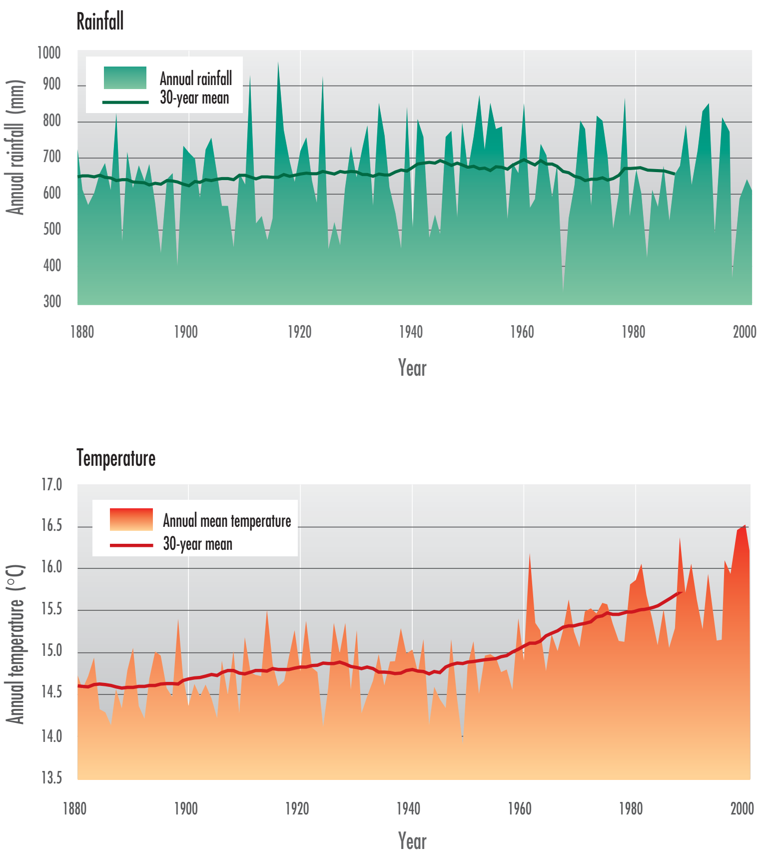


Figure 23. The historical record of annual rainfall (top) and temperature (bottom) for Melbourne. The 30-year running mean is also shown. It is evident that while there appears to be no significant long-term trend in rainfall, there is an apparent significant warming trend since the 1950s.

Changes in urban climate

The Urban Heat Island (UHI) refers to the observation that towns and cities tend to be warmer than their rural surroundings due to physical differences between the urban and natural landscapes. The concrete and asphalt of the urban environment tend to reduce a city's reflectivity compared with the natural environment. This increases the amount of solar radiation absorbed at the surface. Cities also tend to have fewer trees than the rural surroundings and hence the cooling effects of shade and evapotranspiration are reduced. The cooling effects of winds can also be reduced by city buildings.

The UHI is enhanced by human activities within the urban environment. Pollution has a warming effect on a city, in addition to the heat released by industrial processes, household heating and car use. As cities grow, the UHI effect becomes stronger, creating an artificial warming trend in the temperature record. Melbourne's historical temperature record shows rapid increases from the 1950s, at least partly due to increased urbanisation and car use (Figure 23).

The UHI is most noticeable during clear, still nights when rural areas are most effectively able to radiate the heat gained during the day back to space, while the urban environment retains a greater proportion of heat (Figure 24). Depending on the weather conditions, overnight temperatures in the centre of a large city can be up to 10°C warmer than the rural surroundings. The urban landscape has other impacts on the local climate, such as reduced average wind speed due to the blocking effect of buildings and greater frequency of flash flooding owing to the higher proportion of ground sealed with concrete and asphalt and a corresponding reduction in natural drainage.

Nuclear winter

One of the largest potential influences on future climate is the threat, now generally believed to have receded, of a nuclear winter resulting from the enormous increase in smoke and dust in the atmosphere that would follow a nuclear holocaust. Calculations of the potential characteristics of the nuclear winter

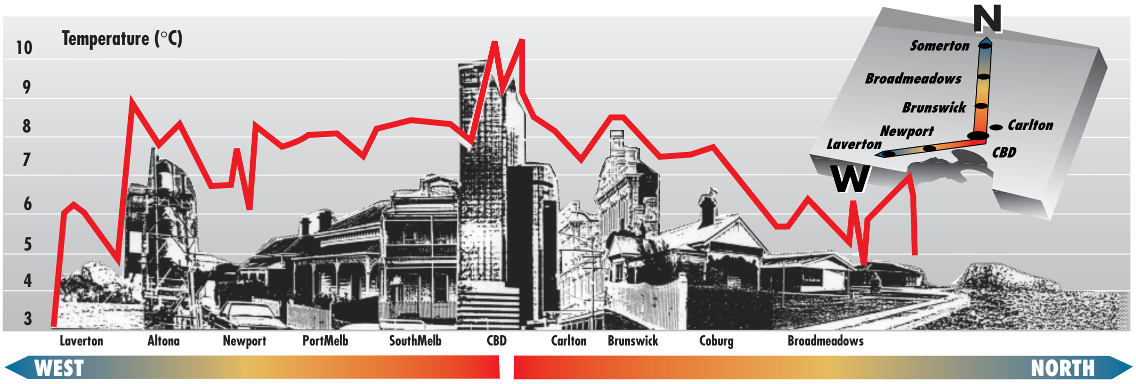


Figure 24. Temperatures across Melbourne on a still and clear night.

have been performed for a range of nuclear war scenarios. A nuclear war would probably have the most sudden and disastrous impact on climate of which humanity is at present technologically capable. A somewhat similar and equally catastrophic effect could be expected to follow from earth's collision with a major asteroid or comet.

Over the past two decades, the evidence for a continuing build-up of carbon dioxide and other greenhouse gases as a result of human activities has become conclusive. These changes have come about as a combined effect of increases in emissions, such as fossil fuel burning, and decreases in sinks, such as reduced forest cover.

Anthropogenic sources of greenhouse gases

More than a hundred years after the first scientific explanation of the earth's natural greenhouse effect and sixty years after the Swedish scientist Svante Arrhenius first calculated the additional warming that might be expected from increased carbon dioxide in the atmosphere (1895), the distinguished US oceanographer and meteorologist Roger Revelle forcefully drew attention to the problems ahead: 'Mankind, in spite of itself, is conducting a great geophysical experiment unprecedented in human history. We are evaporating into the air the oil and coal and natural gas that has accumulated in the earth for the past 500 million years.....This might have a profound effect on climate.'

The concerns of Revelle and others were instrumental in the initiation, in 1957, of what was arguably the most important single geophysical record ever established: the ongoing monitoring of the atmospheric concentration of carbon dioxide in the free atmosphere on the top of Mauna Loa, Hawaii (Figure 25).

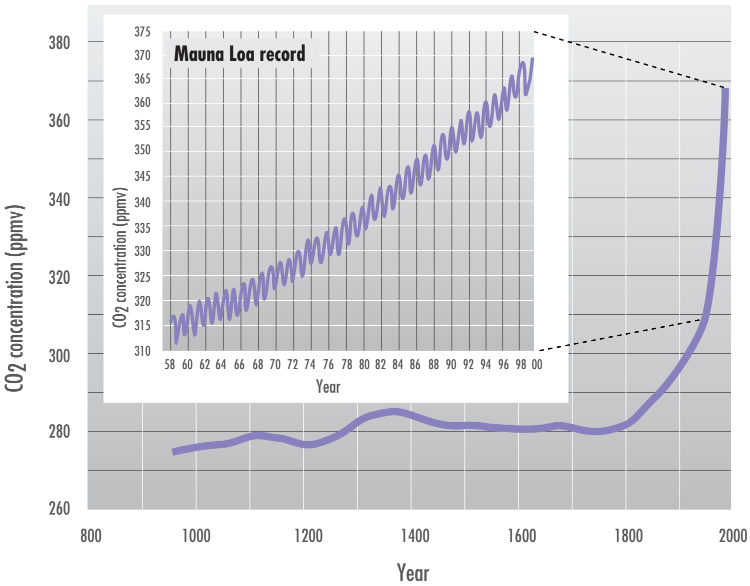


Figure 25. The change in the atmospheric concentration of carbon dioxide over the last 1000 years, based on ice core analysis and, since 1958, on direct measurements. Inset is the monthly average concentration of carbon dioxide (in parts per million by volume) since 1958 at Mauna Loa, Hawaii.

Table 2. Greenhouse gases influenced by human activities.

Greenhouse gases	Principal sources	Sinks	Lifetime in atmosphere	Atmospheric concentration (1998)	Annual rate of growth (1998)	Proportional contribution to greenhouse warming
Carbon dioxide (CO_2)	Fossil fuel burning, deforestation, biomass burning, gas flaring, cement production	Photosynthesis, ocean surface	5 to 200 years	365 ppmv	0.4%	60%
Methane (CH_4)	Natural wetlands, rice paddies, ruminant animals, natural gas drilling, venting and transmission, biomass burning, coal mining	Reaction with tropospheric hydroxyl (OH), removal by soils.	12 years	1745 ppbv	0.4%	20%
Halocarbons (includes CFCs, HFCs, HCFCs, perfluorocarbons)	Industrial production and consumer goods (e.g., aerosol propellants, refrigerants, foam-blowing agents, solvents, fire retardants)	Varies (e.g., CFCs, HCFCs: removal by stratospheric photolysis, HCFC, HFC: reaction with tropospheric hydroxyl (OH))	2 to 50,000 years (e.g., CFC-11: 45 years, HFC-23: 260 years, CF_4: >50,000 years)	Varies (e.g., CFC-11: 268 pptv, HFC-23: 14 pptv, CF_4: 80 pptv)	Varies, most CFCs now decreasing or stable but HFCs and perfluorocarbons growing (e.g., CFC-11: -0.5%, HFC-23: +4%, CF_4: +1.3%)	14%
Nitrous oxide (N_2O)	Biological sources in oceans and soils, combustion, biomass burning, fertiliser	Removal by soils, stratospheric photolysis	114 years	314 ppbv	0.25%	6%

Note: ppmv is parts per million by volume, ppbv is parts per billion by volume, pptv is parts per trillion by volume.

The main sources of the emission of the major anthropogenic greenhouse gases are given in Table 2. Any increases in the atmospheric concentrations of the halocarbon species, while still present only at low levels relative to other greenhouse gases, have a large impact on the level of surface warming owing to their radiation absorption characteristics.

The changes in atmospheric concentration of methane and nitrous oxide over the past 1000 years, shown in Figure 26, have followed much the same pattern as carbon dioxide.

Figure 26 also introduces the concept of radiative forcing which is a measure of the net vertical irradiance due to a change in the internal or external forcing of the climate system, such as a change in the concentration of carbon dioxide or the output of the sun. A positive radiative forcing indicates a warming effect while a negative forcing signals a cooling effect.

Enhanced greenhouse effect

Any changes in the relative mix and atmospheric concentration of greenhouse gases, whether natural or human-induced, will lead to changes in the radiative balance of the atmosphere, and hence the level of greenhouse warming.

Calculations with global climate models have drawn clear links between increased concentrations of greenhouse gases and large-scale surface warming and other changes of climate. It seems likely that, through the 21st century, enhanced radiative forcing by increases in these gases will have a significant influence on global climate, including a detectable warming 'signal' above and beyond the 'noise' of natural variability.

The scientific basis for expectation of an enhanced greenhouse effect is conceptually simple. Increased concentrations of the radiatively-active gases (such as carbon dioxide) increase the

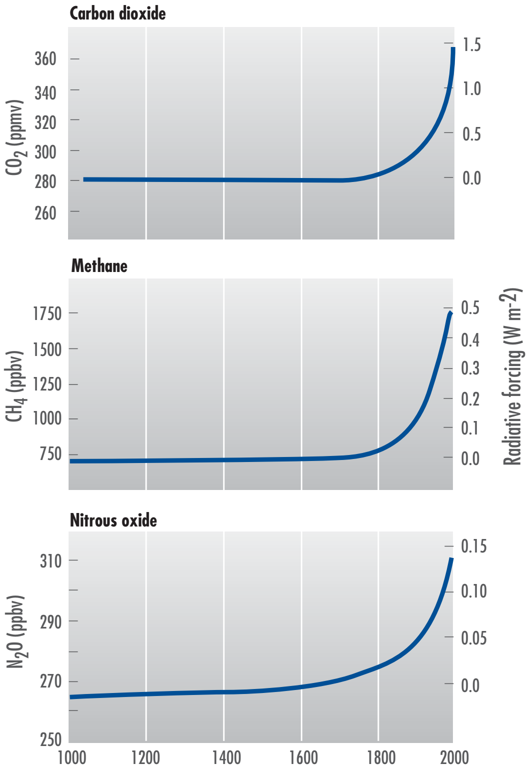


Figure 26. Trends in the atmospheric concentrations of the main well-mixed greenhouse gases over the last 1000 years. The effect that the increased concentrations should have in decreasing the long wave radiation lost to space is shown on the right of the figure in watts per square metre (W m^{-2}).

opacity of the lower atmosphere to radiation from the surface. Therefore, the lower atmosphere absorbs and re-emits more radiation. Some of this is directed downwards, increasing the heating of the surface. This heating continues until a new equilibrium temperature profile is established between the upward surface radiation and downward solar and long wave radiation (Figure 27).

Aerosols and other pollutants

Tropospheric aerosols (i.e. microscopic airborne particles) influence the radiative balance of the atmosphere and thus the climate. These aerosols result both from natural sources, such as forest fires, sea spray, desert winds and volcanic eruptions, and from human causes, such as the burning of fossil fuels, deforestation and biomass burning. They can impact on the radiative flux directly, through absorption and scattering of solar radiation, or indirectly, by acting as nuclei on which cloud droplets form. This in turn influences the formation, lifetime and radiative properties of clouds. Concentrations of tropospheric aerosols vary greatly in space and time and can have either a heating or cooling effect depending on their size, concentration, and vertical distribution.

The cooling effect of aerosols from sulphur emissions may have offset a significant part of the greenhouse warming in the northern hemisphere during the past several decades. Because of their relatively limited residence time in the troposphere, the effect of aerosol pollutants from indus-

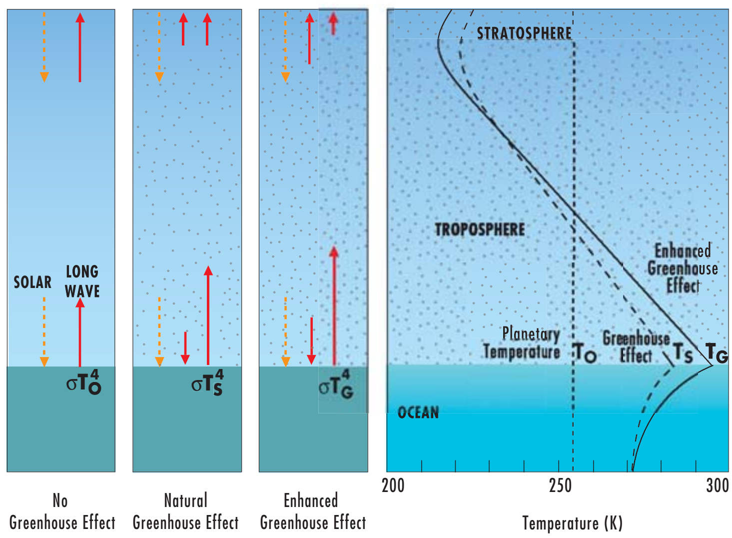


Figure 27. A schematic illustration of the enhanced warming of the surface and lower atmosphere and of the ocean that would be expected to follow from an increase in infrared opacity of the lower layers, i.e. an enhanced greenhouse effect. With increased downward radiation, the surface heats up from T_S to the new temperature T_G at which the upward radiation just balances the sum of the downwards solar radiation and the increased downward infrared radiation. T_0 is the planetary temperature of 255K (cf. Figure 5).

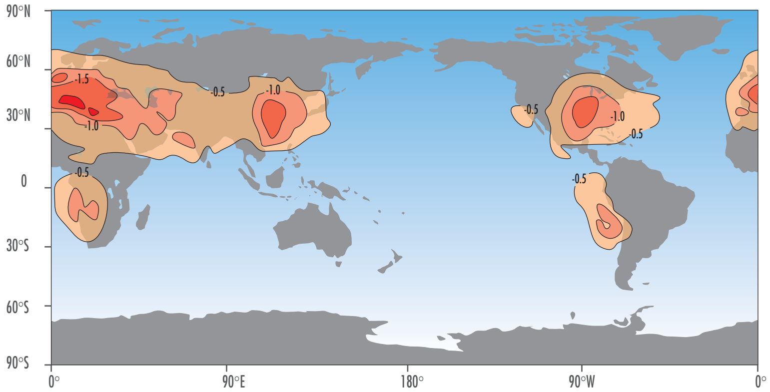


Figure 28. The modelled geographic distribution of annual mean direct radiative forcing (Wm^{-2}) from anthropogenic sulphate aerosols in the troposphere. The negative radiative forcing, which corresponds to a cooling effect on the atmosphere, is largest over or close to regions of industrial activity.

trial processes and forest burning is largely at the regional level (Figure 28). With the pollutant load on the atmosphere generally continuing to increase, the impacts of aerosols on climate will continue to be significant.

Global radiative forcing

Analysis of the global and annually-averaged radiative forcing since the pre-industrial period of the mid-1700s (Figure 29) shows the clear dominance of greenhouse-gas-related warming. However it is also evident that the combined direct effects of tropospheric aerosols have probably provided a significant offset to this warming.

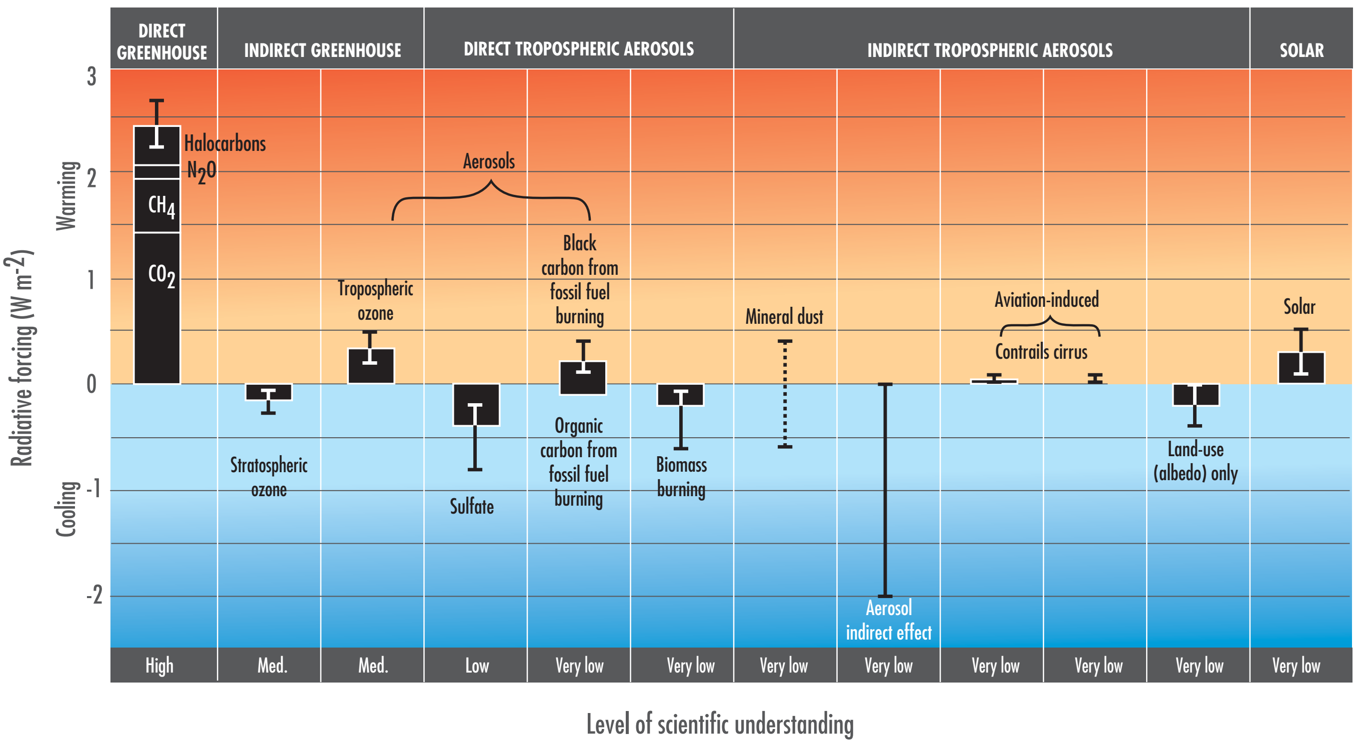


Figure 29. The contribution of various agents to global, annual-mean radiative forcing (Wm^{-2}) since the mid-1700s. The vertical lines about the bars indicate the range of uncertainty and the words across the bottom axis indicate the level of scientific understanding underpinning each of the estimates.

Observing the climate

The processes just described are the major determinants of the present day patterns of climate over the globe. The previous sections also highlight the inherently international nature of climate. As climate knows no political boundaries, understanding it requires a cooperative international effort. This is particularly the case for understanding climate at a global scale where systematic and comprehensive global observations are required.

Our understanding of climate on all scales, from local to global, benefits from the extensive monitoring networks established and maintained by National Meteorological Services around the world, under the coordination and free data exchange principles of the World Meteorological Organization (WMO). A key component of those networks is the WMO World Weather Watch (Figure 30).

In 1992, recognising the need for additional climate data and information to address the issue of climate change and its possible impacts, the WMO, together with the United Nations Environment Programme (UNEP), the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the International Council for Science (ICSU), established the Global Climate Observing System (GCOS).

It is usual to describe the climate in terms of long-term (by convention 30-year) averages and various measures of the variability of temperature, rainfall, cloudiness, wind speed and other elements for particular months or seasons or for the year as a whole. But, as shown in Figure 23 for Melbourne, there can be significant secular shifts even in the 30-year means. Consequently, the choice of period used to calculate a climate normal depends on the application.

Global patterns of mean temperature and rainfall

The annual average temperature distribution over the globe (Figure 33) shows the influence of the various mechanisms already described. Note, for example, the strong poleward temperature decrease in both hemispheres (as follows from the spherical geometry) and the fact that, over virtually the entire globe, the surface temperature is well above the planetary

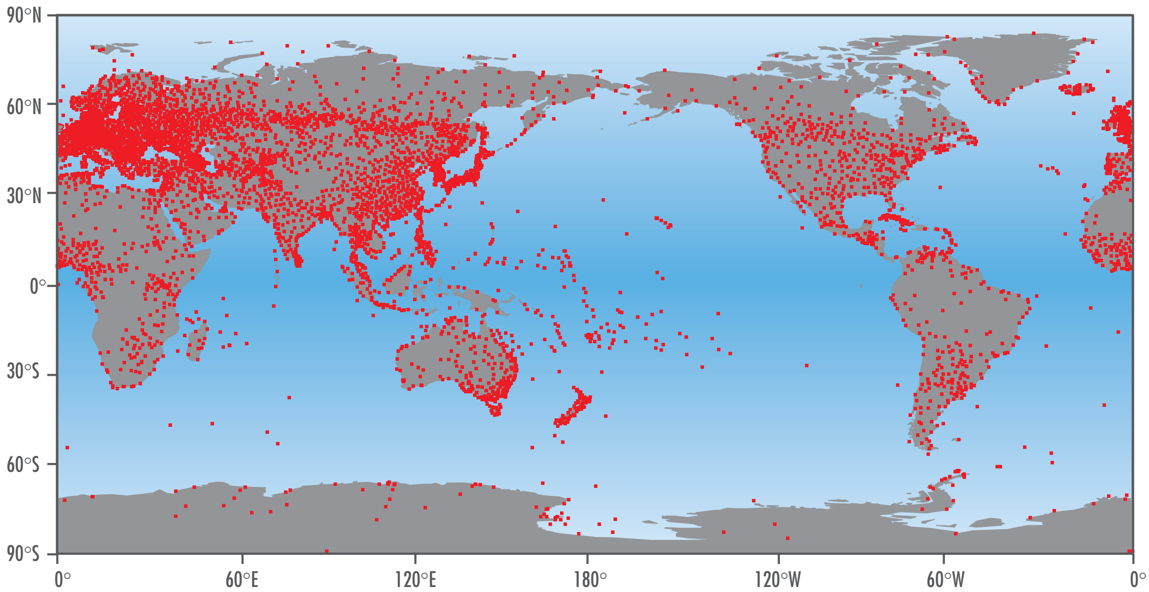


Figure 30. The surface synoptic observing network of the WMO World Weather Watch comprises some 3000 stations reporting between two and eight times daily.

Global Climate Observing System

The Global Climate Observing System (GCOS) is an international program established to ensure that the observations required to address global climate issues are obtained according to international standards and made available to all potential users. It is intended to be a long-term system capable of providing the data required for monitoring the climate system, detecting and attributing climate change, assessing the impacts of climate variability and change, and supporting research toward the improved understanding, modelling and prediction of the climate system.

Primarily, GCOS is based on existing observation networks, such as the Global Observing System of the WMO World Weather Watch and the Integrated Global Ocean Services System (IGOSS). It addresses the total climate system through partnerships with other observing systems such as the Global Ocean Observing System (GOOS) for physical, chemical and biological measurements of the ocean environment, the Global Terrestrial Observing System (GTOS) for land surface ecosystem, hydrosphere and cryosphere measurements, and the WMO Global Atmosphere Watch (GAW) for atmospheric constituent measurements.

One of the key components of GCOS is the GCOS Surface Network (GSN) (Figure 31). The GSN is designed to provide sufficient data for the detection of the spatial patterns and scales of temperature change at the surface of the globe and also for detecting changes in atmospheric circulation. However, the network is not sufficiently dense to support the analysis of highly spatially variable elements such as precipitation. Another key component of the system is the GCOS Upper-Air Network (GUAN) (Figure 32). Its purpose is to ensure a relatively uniform distribution of upper-air observations over the globe suitable for detecting climate change in the upper atmosphere. In selecting observation stations for these networks, existing stations with reliable, long-term records, and expected future continuity, were preferred.

GCOS is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the United Nations Environment Programme (UNEP) and the International Council for Science (ICSU).

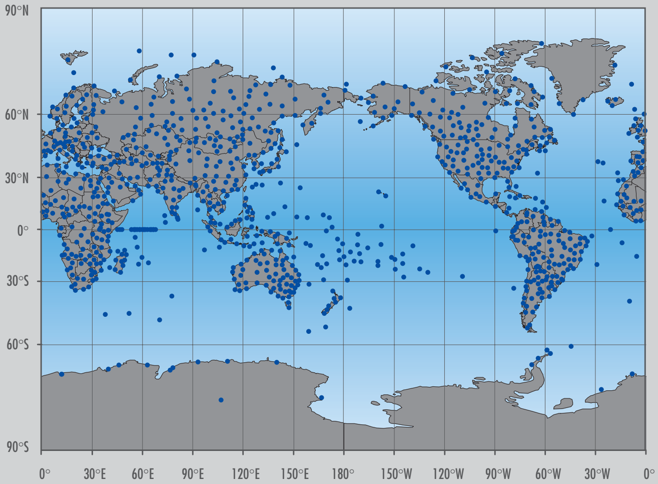


Figure 31. Spatial distribution of the GCOS Surface Network.

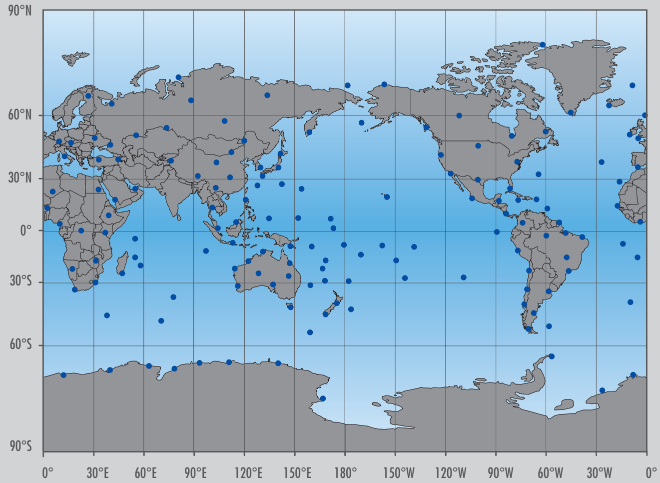


Figure 32. Spatial distribution of the GCOS Upper-Air Network.

radiative temperature (the influence of the greenhouse effect). The strong east-west contrasts of temperature, in the Pacific Ocean in particular, derive from the influence of the continent boundaries on the ocean circulation generated by the prevailing zonal (i.e. latitudinal) winds in the high latitudes.

The long-term annual mean pattern of rainfall over the globe is shown in Figure 34. The strong influence of the mean meridional (i.e. north-south) circulation is evident in the location of the desert regions in the latitudes of the descending air of the Hadley cells of both hemispheres.

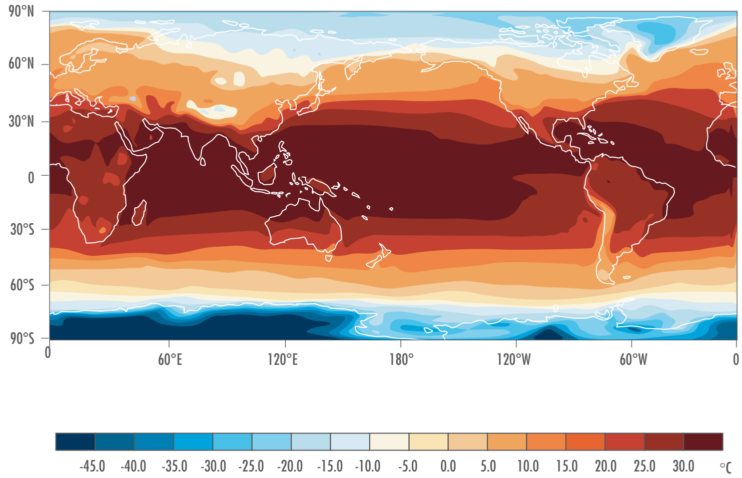


Figure 33. The thirty-year (1961-90) annual mean (i.e. normal) surface temperature (°C) over the globe.

The range of climate zones

As is evident from Figures 33 and 34, the warmer regions of the world span an enormous range of annual mean rainfall, from tropical rainforests to arid deserts. In the colder climates, the rainfall is generally lower and not quite so spatially variable. While there is much more to climate than annual means, it is useful to examine the range of climates over the globe in terms of annual mean temperature and rainfall (Figure 35). Australian climate zones are shown as a subset. While a few sites (e.g. in the cool but extremely wet climates of western Tasmania) fall just outside the boundaries shown, the vast majority of the world's climates fall within. It is evident that people and ecosystems have adapted to a wide range of climate zones throughout the world.

The great spatial variability of Australian climate is also evident in the average annual rainfall throughout the country (Figure 36). On average, much of inland Australia experiences less than 300 mm of rain per year while on the Queensland coast near Cairns and in parts of western Tasmania, annual rainfall averages over 3000 mm.

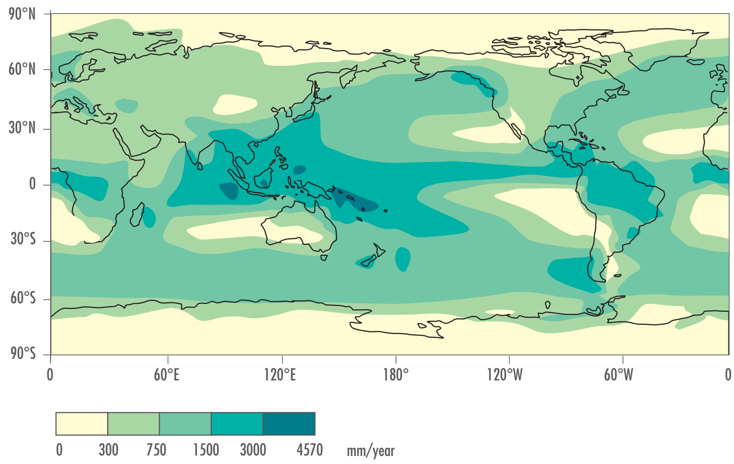


Figure 34. The thirty-year (1961-90) pattern of annual mean rainfall over the globe (mm).

High-quality climate data

High-quality data at both regional and global scales are critical to the identification of real trends or changes in climate variables. Not only is it important to know how climate has varied (on seasonal to decadal time-scales) and changed (on decadal to eon time-scales) in the past, high quality data are essential in efforts to identify the reasons that the climate changed. The validation and refinement of climate models also depends on high-quality observations of 'real' climate, both past and present.

In historical terms, the length of the instrumental record is relatively brief. On a global scale, it extends back no further than the 1860s. Interpretation of trends within this record is further complicated by the fact that most long instrumental records contain non-climatic discontinuities or inhomogeneities.

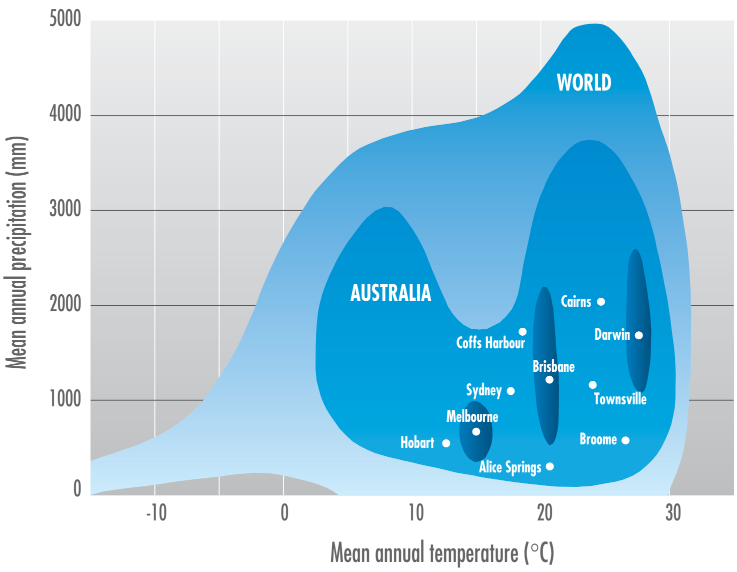


Figure 35. The range of climate regimes of the world presented in terms of mean annual temperature and precipitation. The inner shaded area covers essentially all the climate regimes of Australia. The warm rainfall peak corresponds to parts of the Queensland northern coast while the cooler peak relates to the heavy rainfall areas on the Tasmanian west coast. For Melbourne, Brisbane and Darwin the chart also shows the envelope of the annual means for all of the individual years in the climate record.

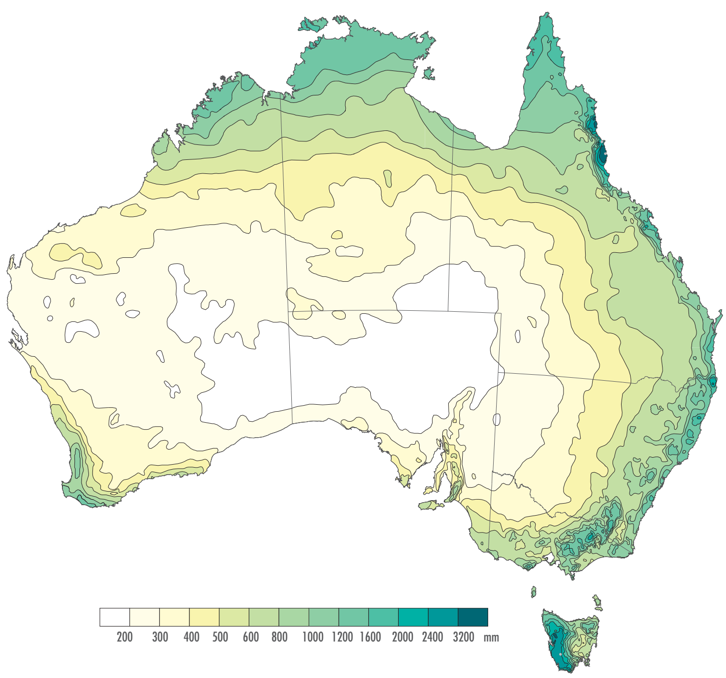


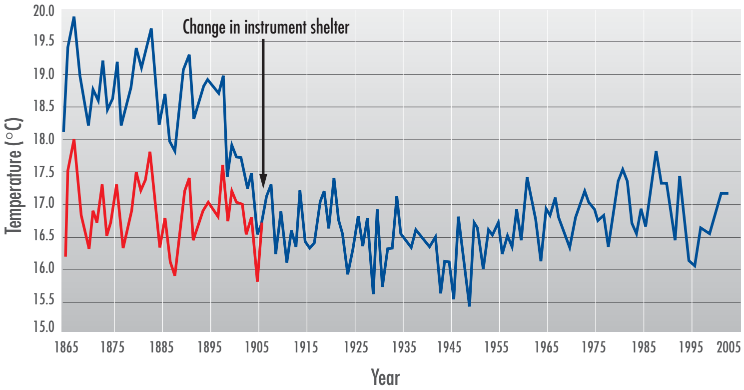
Figure 36. Average annual rainfall for Australia - based on the 30-year period 1961-90.

Any change in location, exposure, instrumentation (Figure 37) or observation practice has the potential to create an artificial discontinuity in the climate record of an observation site. For instance, changes in the exposure of instruments, such as through new buildings or growth of trees, can cause apparent differences in temperature and other climatological variables. The changeover from imperial to metric measurement systems may have also induced discontinuities in recorded data. Even slight changes, while hard to detect in day-to-day observations, can create an apparent shift in the observed climate of the site when monthly or annual mean values are calculated. The magnitude of these artificial jumps can be as large as, or larger than, the changes caused by natural variability or changes associated with greenhouse warming. Therefore, they can create spurious trends in the data and make it difficult to detect real climate trends.

A common technique used to correct discontinuities in a climate record involves comparing the series to be homogenised with a highly-correlated homogeneous reference series. The candidate series is then adjusted at the dates of discontinuity so that the difference between the two series remains constant throughout the record. Often, dates of potential discontinuity can be identified using graphical or statistical techniques, or by examining station history information (metadata). In recent times, parallel observations over a few years or more are often taken before a change is made at important climate sites. This allows the climate impact of the change to be determined, and the climate record to be adjusted to allow for the change. Often climate trend analyses are based on an average of numerous stations, such as a regional network, to allow random biases at individual stations to cancel each other out, leaving the true climatic signal. This is the approach used for calculating the global mean temperature. No single climate record should be used as evidence for or against global warming.

Further improvement to the quality and both spatial and temporal extent of past climate data is taking many forms. This includes 'cleaning up' instrumental data, through a process of 'data rehabilitation', in

Figure 37. Annual mean temperature series at Cape Otway, Victoria showing the differences between temperatures in the early part of the record, measured using a Glashier stand, and temperatures measured using the current standard instrument shelter, a Stevenson screen. Once the data are corrected for this bias, as shown by the red line, the overall trend tells a remarkably different story. Gaps in the record have also been filled by estimating values from comparisons with highly-correlated neighbouring station records.



order to retrieve useful information from data of widely varying quality. A priority is given to continuous long-term records of observations from individual locations. Acquisition of more proxy data (e.g. tree rings, ice core data) is also important, both to provide wider global coverage of past observations and to extend the record as far back in time as possible. The speculation raised by the Greenland ice cores, for example, concerning the possibility of rapid climate oscillations during the Eemian period, may be clarified with subsequent data.

Ongoing maintenance of current climate observation networks is essential for detailed, global climate changes to be monitored. This is both to test the validity of climate projections and to monitor the effect of emission reduction strategies. The promotion of national Reference Climate Station networks by the World Meteorological Organization and the Global Climate Observing System (GCOS) are vital initiatives. Australia maintains high quality reference networks for temperature (Figure 38) and rainfall (Figure 39), and the Bureau of Meteorology gives high priority to ensuring that these stations adhere to the standards and principles stipulated by the GCOS.

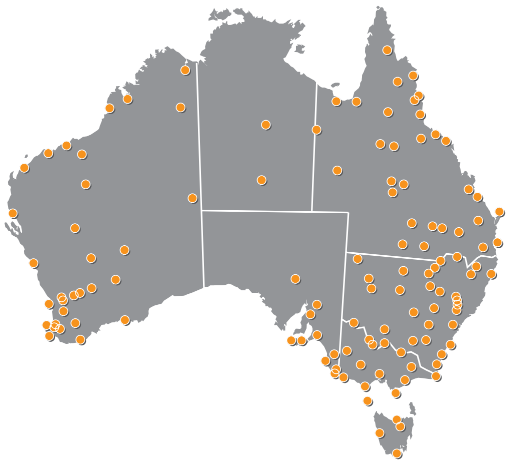


Figure 38. The Australian high-quality temperature network, the requirements for which include long continuous, homogeneous observations from the same site for generally 90 years.

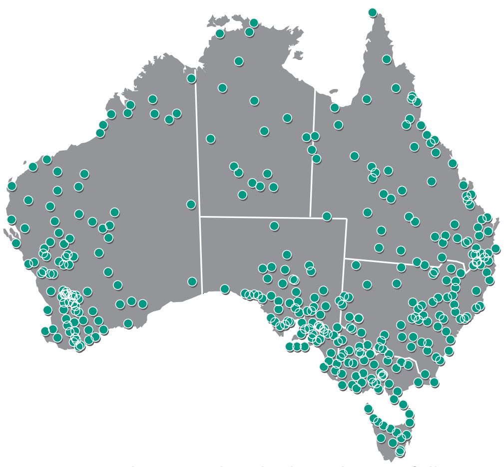


Figure 39. The Australian high-quality rainfall network, the requirements for which include long continuous, homogeneous observations from the same site for generally 100 years.

Recent climate trends

The period over which instrumental observations of climate variables have been accumulated on a global scale, albeit with patchy distribution and mixed quality, extends back in time little more than one century. Given the many internal and external forces driving natural climate variability, detection of any anthropogenic trends or changes which may be superimposed upon this signal over such a limited period is a challenge. It is important to note that the inability to detect a trend does not necessarily imply that one does not exist; it may reflect the inadequacy of data or the incomplete analysis of data. This applies especially to global trends of variables with large regional variability, such as precipitation.

Temperature changes

Analysis of the observed climate records has revealed increases in global mean surface air temperatures, over land and sea combined, of 0.4 to 0.8°C since the late 19th century. This range accounts for estimated uncertainties associated with instrumental bias and urbanisation. Most of this increase has occurred in two periods, from 1910 to 1945 and since 1976. Figure 40 presents a time series of global mean surface temperatures for the duration of the instrument record. While this represents global averages, the warming has not been globally uniform. In recent decades, the warming has been greatest over the continental northern hemisphere at latitudes between 40°N and 70°N.

During the last decade or so, global annual mean surface temperatures have been among the warmest on the instrumental record. The global mean temperature for 1998 made it the warmest year ever recorded and the 1990s were the warmest decade. This is despite the relatively cooler temperatures recorded in 1992 and 1993 which have been attributed to the cooling effect of stratospheric aerosols from the eruption of Mt Pinatubo in 1991.

Generally, both day and night temperatures have risen, although night-time temperatures have generally warmed more than daytime temperatures. As a consequence, the daily temperature range is decreasing. The reason for the larger increase in overnight temperatures is not clear but there is some evidence that it is associated with increases in cloud cover. The urban heat island effect would have some impact on overnight temperatures but the increases are observed widely over both rural and urban areas.

The annual mean temperature series over Australia is generally consistent with the global trend in showing warming, particularly in recent decades (Figure 41). However, this warming trend is not uniform throughout the country, nor is it the same for maximum and minimum temperatures (Figure 42). As for many parts of the globe, the increase in mean minimum temperatures over the period is markedly greater than the mean maxima, especially for the period since 1950. The areas showing the greatest increases in minimum temperature, with trends of more than 2°C per century, are in inland Queensland, well away from urban areas. These analyses are based on a high-quality, non-urban temperature network (Figure 38).

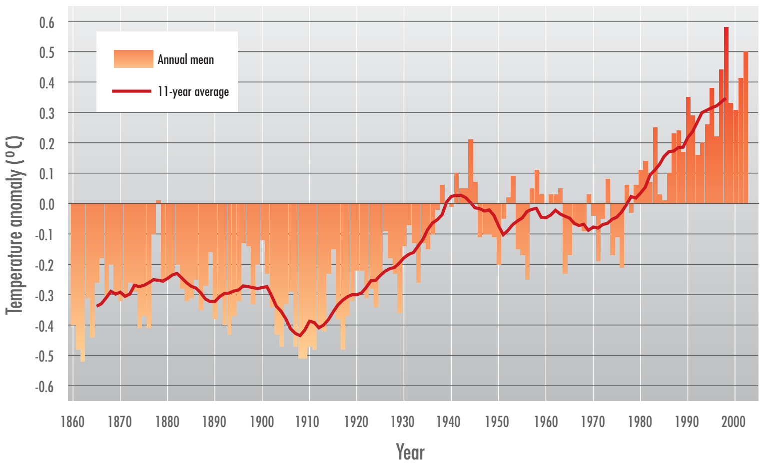


Figure 40. Global mean land and sea-surface temperature anomalies for the duration of the instrumental record.

Precipitation changes

Enhancement of the greenhouse effect may lead to changes in the hydrological cycle, such as increased evaporation, drought and precipitation, and it is likely that such changes would have a higher regional variation than temperature effects. Unfortunately, inadequate spatial coverage of data, inhomogeneities in climate records, poor data quality and short record lengths have hampered attempts to come to terms with the current state of the hydrological cycle. Understanding and modelling all the climate processes and feedback effects that are influenced by the cycling of water through

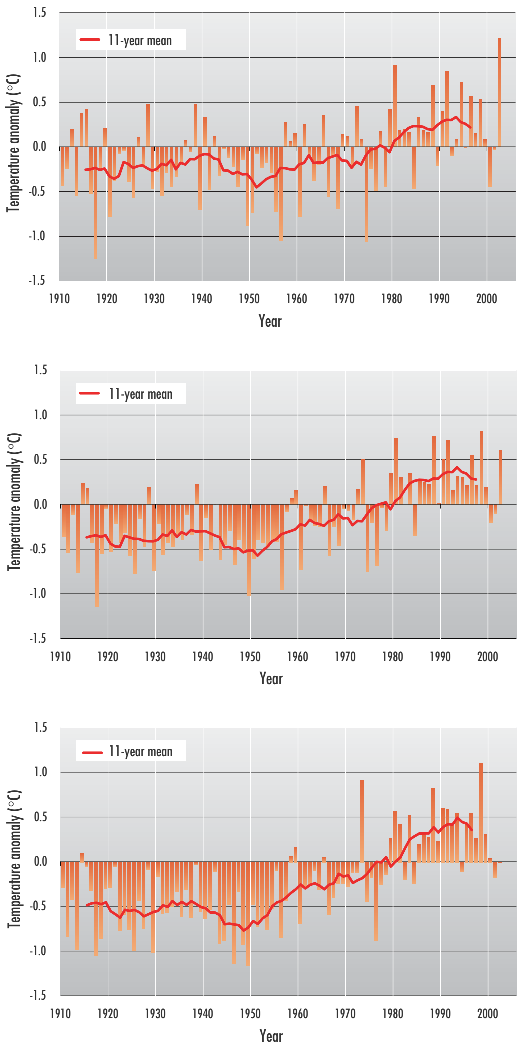


Figure 41. Annual averaged maximum (top), mean (middle) and minimum (bottom) temperature anomalies (departures from the 1961-90 mean) for Australia for the period 1910 to 2002. The analysis is based on a high quality dataset comprising records from approximately 130 stations across Australia.

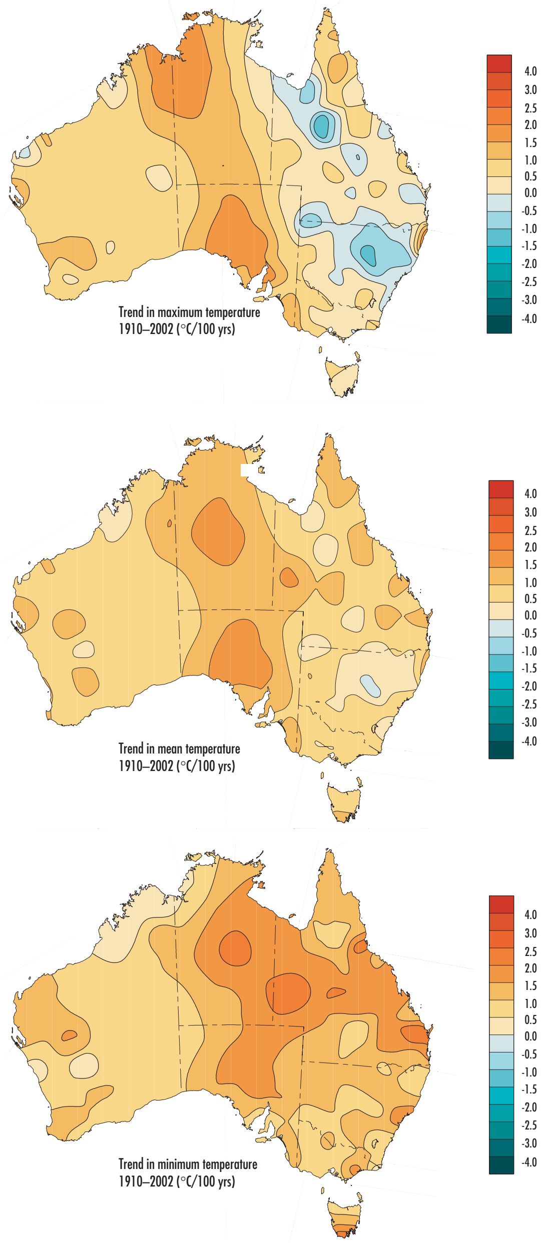


Figure 42. Trends in annual maximum (top), mean (middle) and minimum (bottom) temperature over Australia during the period 1910 to 2002. Contour interval is 0.5°C per century.

the climate system makes the prediction of precipitation changes equally difficult.

Analysis of the data that are available reveals that, averaged over land areas, there has been a slight increase in precipitation over the 20th century of about 1%. However, precipitation over land has decreased substantially in the last two decades. Regional increases have been detected in the high continental latitudes of the northern hemisphere and more recently decreased rainfall has been observed over parts of the northern hemisphere subtropics. Direct observations and model analyses indicate that rainfall has also increased over large parts of the tropical oceans. It is more difficult to calculate global mean values for rainfall than for temperature. This is because of the large spatial variability of rainfall, requiring a much denser observation network to achieve a realistic mean value. In areas where sufficient data exist, cloud amount has generally increased since the 1950s over both land and the ocean.

The time series of Australian mean annual rainfall shows a weak increase over the 20th century (Figure 43). However, this trend is dominated by large interannual variations, at least partially due to fluctuations associated with the El Niño - La Niña cycle. This increase has not been uniform, with the strongest increases being in the far Northern Territory and parts of the New South Wales coast (Figure 44). The southwest tip of Western Australia, southern Tasmania and east-central Queensland actually show a decline in rainfall over the century. Figure 45, which isolates the trends for 1950-2002, is an interesting comparison and demonstrates the scale of inter-decadal variation in rainfall. While the drying trends evident in the overall (1900-2002) record are clearly observed in the 1950-2002 subset, the long-term rainfall increases over eastern New South Wales for the period as a whole are not evident over the latter half century. The latter drying trends are possibly associated with the local impact of strong El Niño events over recent decades and highlight the importance of viewing climate trends over appropriate long-term time frames.

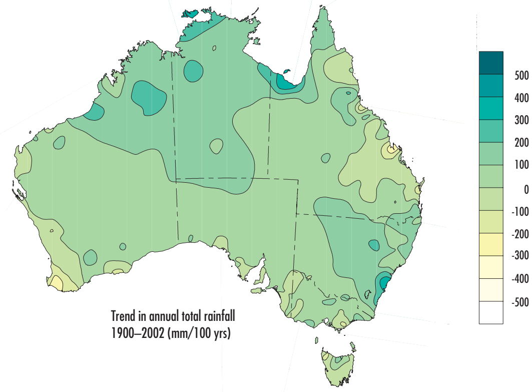


Figure 44. Trend in Australian mean annual rainfall (mm per year) over the period from 1900 to 2002.

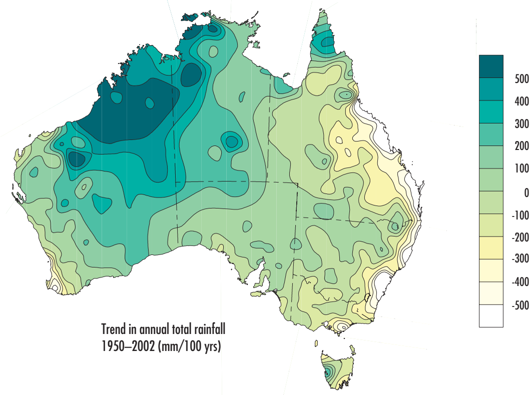


Figure 45. Trend in Australian mean annual rainfall over the period 1950 to 2002 demonstrating the impact of inter-decadal variations.

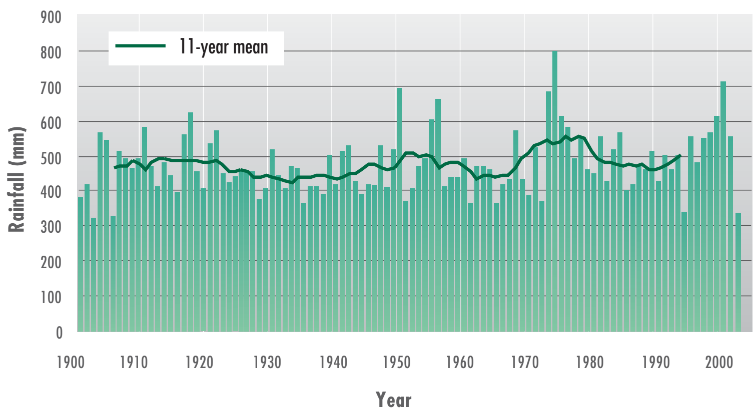


Figure 43. Time series of Australian mean annual rainfall 1900-2002.

Atmospheric/oceanic circulation changes

The long-term historical record of the El Niño - La Niña cycle indicates that El Niño events have occurred in the past on a loosely regular basis with a return period of between 3 and 8 years. An apparent discontinuity in this behaviour occurred around 1976, with more frequent El Niño episodes at least up until the late 1990s. The excursions to the other extreme (La Niña episodes) have occurred less frequently since 1976, albeit an extended series of weak La Niña episodes occurred between 1998-99 and 2001-02 (Figure 46). This behaviour, especially the recurring El Niño events between 1990 and 1995, is unusual in the records of the last 120 years, although a similar period of sustained negative bias in the Southern Oscillation Index occurred in the decades around the turn of the century.

Changes in precipitation over the tropical Pacific Ocean are related to this change in El Niño behaviour. This has also affected the pattern and magnitude of surface temperatures.

Changes in upper-air temperatures

Despite their relatively short record lengths, weather balloon-borne radiosonde observations and satellite measurements indicate that globally the troposphere has warmed and the stratosphere cooled over the last two decades (Figure 47). The global mean temperature trend in the lower troposphere has been calculated to be 0.05 ± 0.10ºC/decade over this period. The equivalent trend at the surface is significantly greater at 0.15±0.5ºC. The reasons for this apparent discrepancy include differences between the spatial coverage of the surface and tropospheric observations, as well as differences between responses to volcanic eruptions and ENSO events at the two levels.

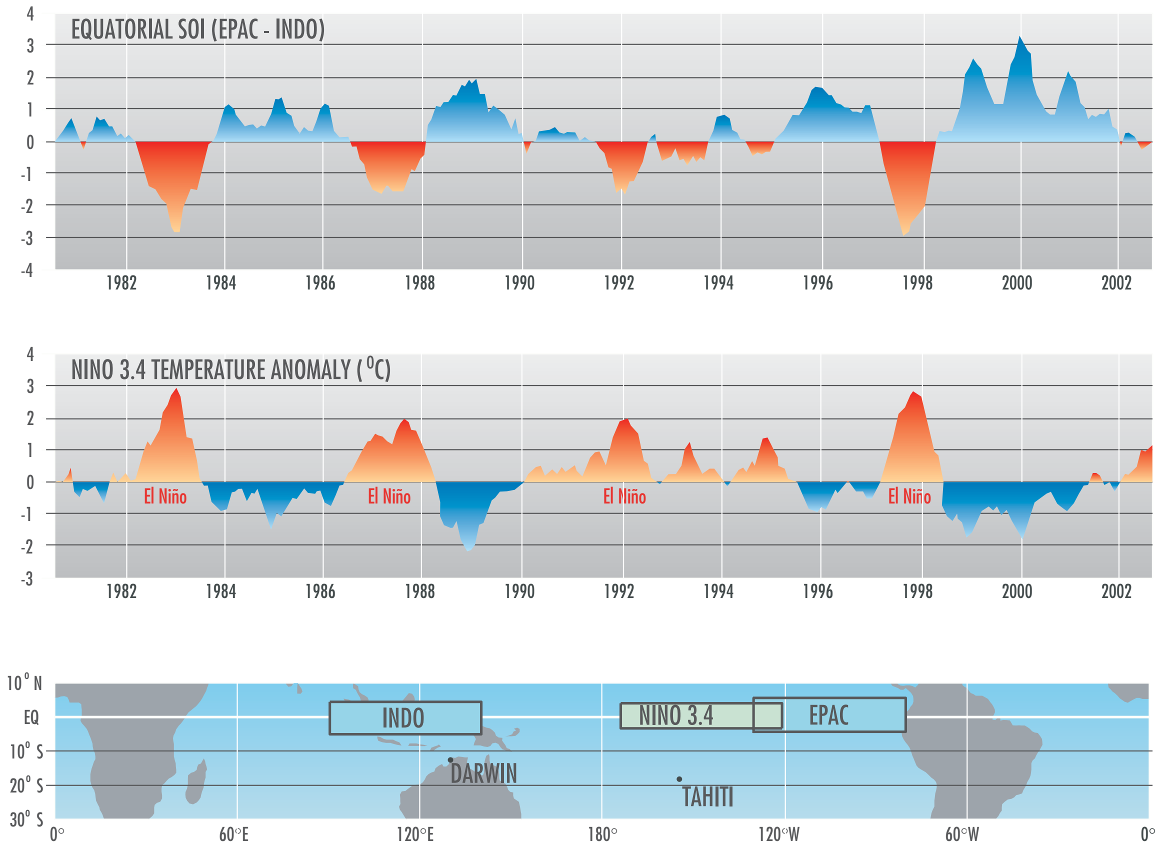


Figure 46. The El Niño and the Southern Oscillation from 1980 to 2002. The upper chart shows the variation in equatorial Southern Oscillation Index, a measure of the difference in surface pressure gradients between the Indonesian region (INDO) and the Eastern Pacific (EPAC). The locations of the regions are defined in the lower chart. In the middle is shown the indicative mean temperature anomaly as recorded in the region designated 'NINO 3.4'.

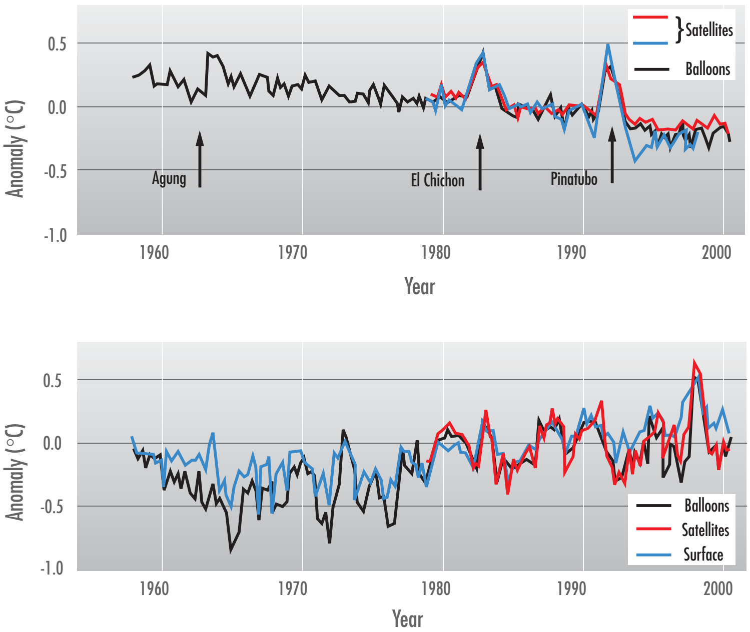


Figure 47. Time series of global temperature anomalies of the stratosphere (top) and troposphere (lower) based on weather balloons and satellite measurements.

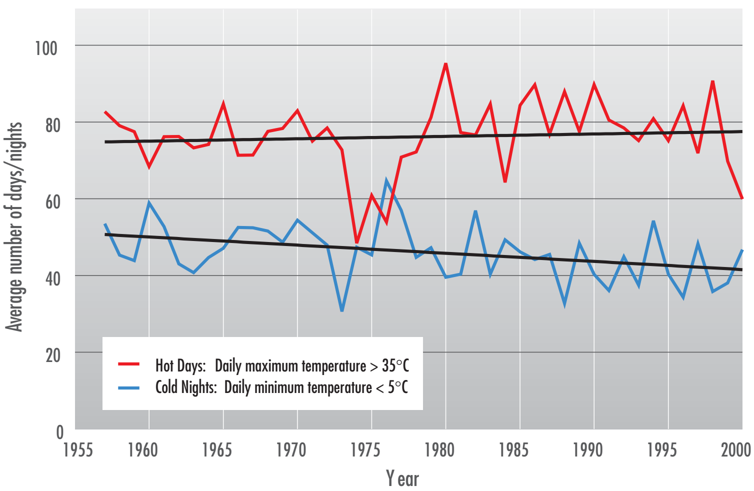


Figure 48. Australian average number of hot days (daily maximum temperature 35°C or greater) and cold nights (daily minimum temperature 5° or less). Note that averages are based on only those observation sites that record daily maxima of 35°C or greater and daily minima of 5° or less.

Changes in extreme events

The most significant impacts of climate on society are associated with its extremes, such as droughts, floods, heatwaves, blizzards and severe storms. However, determining real trends in extreme climatic events is often more difficult than for mean variables because of the extra demands on the quality of the observational data. Analyses of many extremes require data at greater temporal resolution (e.g. at the daily, rather than monthly time-scale) but digitised high-resolution data are generally less available than data at monthly or longer time-scales. Also, when investigating trends at the extreme ends of a climatic distribution, the likelihood of complications due to erroneous data is increased because outliers can be falsely considered as true data extremes. Missing data are also of great concern when considering extreme climate events.

In regions where analyses of extreme precipitation events have been undertaken, the changes in the frequency of extreme events has generally been consistent with changes in the mean rainfall. Thus in regions where total precipitation has increased, the frequency of heavy and extreme precipitation events has also increased. In mid to high latitudes of the northern hemisphere there was a 2 to 4 per cent increase in the frequency of heavy precipitation events over the second half of the 20th century. Over the century there has been a weak increase in the global land areas experiencing severe drought or excess rainfall.

There has been a general trend to fewer extremely low minimum temperatures throughout the globe in recent decades, with corresponding trends toward fewer frost events and shorter frost seasons. Generally, increases in extreme high temperature events have been weaker than the decline in cold extremes. In Australia, changes in extreme temperature events are consistent with changes in mean temperatures; i.e., warming trends in both maximum and minimum temperatures have resulted in weak increases in the numbers of hot days reported and a decline in the number of cold nights (Figure 48).

Globally, the available observational data indicate no significant changes in the intensity and frequency of tropical cyclones and extratropical storms. The frequency of such events tends to be dominated by decadal variability but the records are not long enough to confidently identify long-term trends. Records on the frequency of tropical cyclones in the Australian region (south of the equator between 90° and 160ºE) have been kept since 1908. However, the annual totals for the region are not reliable until the late 1960s when meteorological satellite data became available (Figure 49). The apparent decline in annual numbers during the 1990s is most likely to be associated with more frequent El Niño events during the period. Globally, the overall trend in tropical cyclone numbers is flat, with areas of increased activity offsetting areas of decreased activity from year to year.

In the few studies of trends in local severe weather events that have been undertaken, no clear long-term changes have been identified.

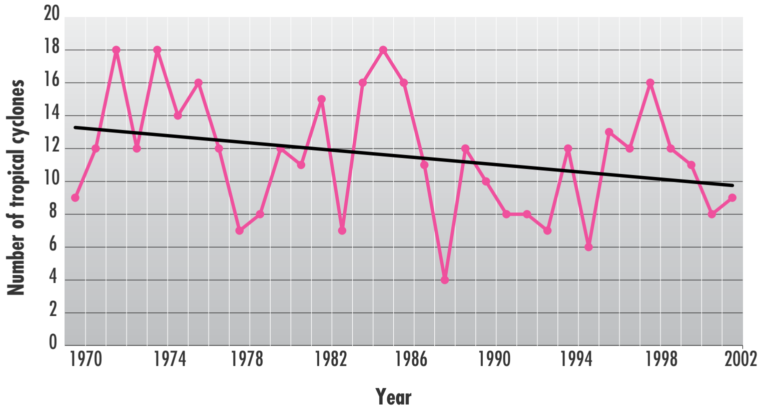


Figure 49. Frequency of tropical cyclones in the Australian region since the 1969-70 season.

Sea-level changes

Based on analyses of tide-gauge records, global mean sea-level has risen by about 10 to 20 cm over the 20th century. However, in estimating the component of the rise that is attributable to the increased volume of seawater, a major source of uncertainty is the influence of vertical land movements which cannot be isolated in tide gauge measurements. Improved data filtering techniques and greater reliance on the longest-term tide gauge records have led to a high degree of confidence that the volume of seawater has been increasing and causing the sea level to rise within the indicated range. Satellite-based instruments now enable near-global sea-level change measurements, although many years of data will be required before reliable trends can be established. Most of the rise in sea level is related to the thermal expansion of the oceans in response to the rise in global temperature over the last 100 years and the retreat of glaciers.

The message from the past

The behaviour of climate in the recent and distant past, and the factors that have driven it to change, provide an important historical context for considering the earth's current climate and possible future climate change. Clearly, any climate changes that occurred prior to the last 150 years or so took place in the absence of any widespread anthropogenic influence.

Proxy data

Direct instrumental observations of climate have only been recorded on a global basis since the middle to late 19th century. The most complete time series of global sea-surface and land temperatures commenced in 1861 although individual records commenced earlier in some areas, for example from 1772 in central England. Prior to this time, and to supplement and corroborate more recent instrumental data, various forms of indirect observations or 'proxy data' are used. Paleo-climatic data are derived from elements of the natural environment whose growth characteristics carry embedded time and climate markers. These data can yield information on climate extending back in time anything from a few hundred, to hundreds of thousands of years. Sources of proxy data include tree rings, pollen records, faunal and floral abundances in deep-sea cores, and isotope analyses from corals and ice cores. Additional direct and proxy data can be derived from diaries and other documentary evidence. Some forms of proxy data, particularly those that individually or in combination have a global distribution, can give indications of worldwide climate, while others can provide quite detailed records of climatic history in specific locations or regions.

Reconstructions of the northern hemisphere temperatures over the past 1000 years show that recent trends determined by instrument are remarkably different to those indicated by the longer term proxy record (Figure 50). A global analysis of proxy data is not possible since the southern hemisphere has a much lower density of proxy data.

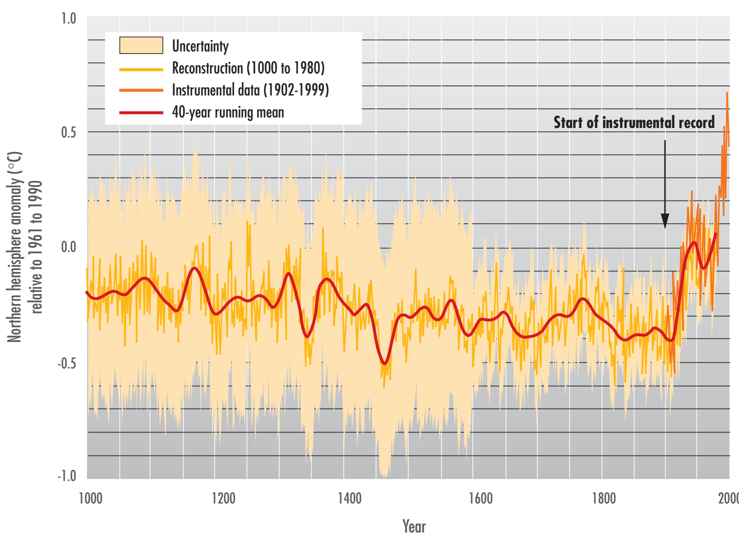


Figure 50. Reconstruction of northern hemisphere temperatures over the past 1000 years based on instrumental and proxy data records.

Last 100 million years

As shown in Figure 51, the earth's climate has clearly exhibited significant variations in the past, on time-scales ranging from many millions of years down to a few decades. Over the last two million years, glacial-interglacial cycles have dominated, occurring on a time-scale of 100,000 years, with large changes in ice-volume, sea level and temperature.

The Eemian Interglacial, some 100,000 years before present (BP), is the closest past analogy of the present interglacial cycle and has been looked to for hints as to how the climate might behave in a greenhouse-warmed world. Analysis of ice cores from the Greenland summit provide a frozen temperature record (via oxygen isotope ratios) downward to 250,000 years BP and suggest that the Eemian Interglacial may have been punctuated by sudden frequent catastrophic reversions to ice age conditions which lasted from a few tens of years to some 6,000 years. Such cores also provide evidence of rapid warming about 11,500 years BP. Central Greenland temperatures increased by about 7°C in a few decades and there are indications of even more rapid changes in the precipitation pattern and of rapid reorganisations in the atmospheric circulation. Changes in sea-surface temperature, associated with sudden changes in oceanic circulation, also occurred over a few decades.

There is firm evidence in northern hemisphere, and possibly global, records of rapid warm-cold oscillations during the last glacial period with rapid warmings of 5 to 7°C in a few decades followed by periods of slower cooling and then a generally rapid return to glacial conditions. The Antarctic record reflects the climate oscillations evident in northern hemisphere records but with magnitudes that are consistently less, typically only 2 to 3°C.

Periods of rapid climate change are therefore not unprecedented in the long-term climate history but there is no evidence that such large changes have occurred in the last 10,000 years of the present interglacial. The physical cause of rapid climate changes such as these is not understood, although one possible mechanism is the shutdown of the North Atlantic conveyor belt (Figure 13). This is frequently suggested as the cause of the Younger Dryas cooling, at the time the earth was emerging from the last ice age some 12,000 years before present. The North Atlantic is clearly an important and dynamic part of the climate system. Evidence from past records and model projections for future climate change indicate that the largest regional climate variations occur in adjacent mid-latitude regions of the northern hemisphere.

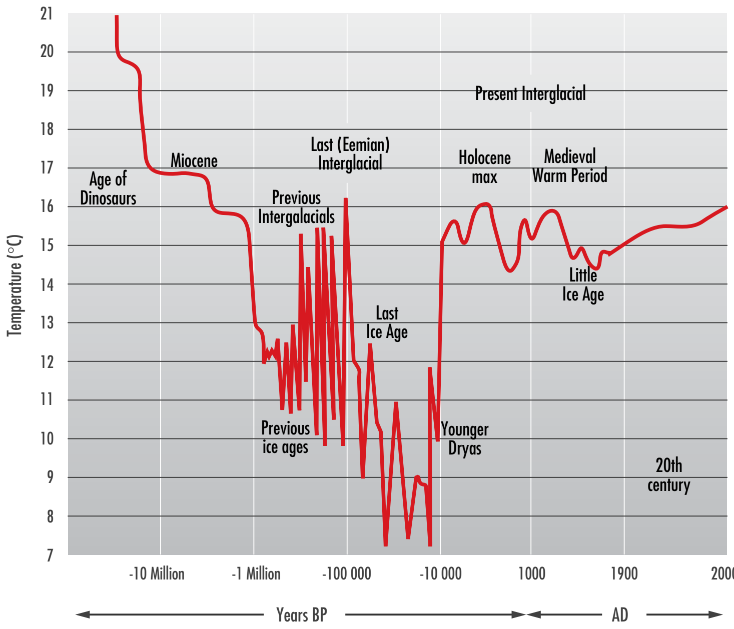


Figure 51. A schematic summary of recent climate trends in historical perspective. The 20th century is shown in linear scale. Earlier periods are shown in terms of increasing powers of ten but are linear within each period.

Holocene

In examining whether climate change has occurred in the last two centuries and whether climate change will continue or even accelerate over the 21st century, we are clearly looking at a very short period of time, even in the context of the 10,000 years of the present interglacial period.

So far, over the 10,000 years since the world emerged from the most recent ice age, the global mean temperature has remained remarkably stable, around 15°C. The globally averaged temperature fluctuations associated with the so-called Climatic Optimum (the Holocene Maximum 4000-7000 years ago), the Medieval warm period in the 11th and 12th centuries and the Little Ice Age, from the 13th to the mid-19th centuries (which may not have been global), appear to have been at most 1-2°C, though the anomalies were obviously much larger in particular regions. There are indications that the mean global rate of temperature rise has not been sustained at greater than 1°C per century at any time during the Holocene era.

Analyses of alpine glacier advance and retreat have provided arguably the most complete summary of global temperatures throughout the Holocene. Figure 52 shows the time series of cold (glaciers more advanced) and warm (glaciers less advanced) periods over the last 10,000 years. The Little Ice Age is presented as a global feature and the warming of the last century is markedly as rapid, if not more rapid, than at any other time throughout the Holocene. Although previously considered to be a global climate feature, recent evidence indicates that the extremes of the Medieval warm period were probably confined to Western Europe and the North Atlantic.

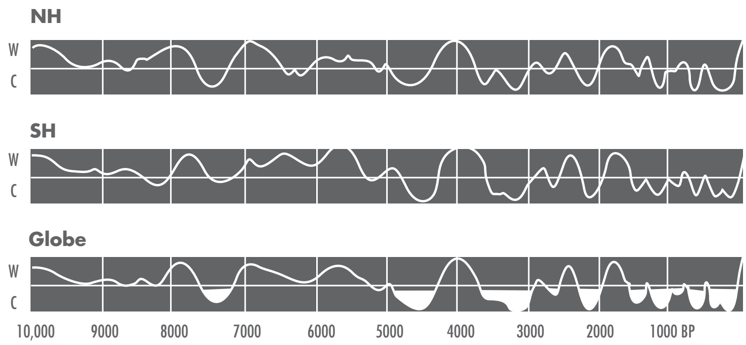


Figure 52. Chronologies of alpine advance and retreat for the northern hemisphere, southern hemisphere and globe. W and C refer to warm (glaciers less advanced) and cold (glaciers more advanced) periods.

Modelling climate and climate change

An essential tool for exploring possible future climate, particularly for producing projections of the long-term global trends that might be expected from the build-up of greenhouse gases, is a model of the climate system. Such a model must incorporate the best-available knowledge of the relevant physical, chemical and biological processes. Confidence in the output of such models depends on their demonstrated ability to represent the major features of the present-day climate realistically, as well as those of the well-documented climates of the past.

Climate models range in type from simple, one-dimensional energy balance models, which can be used to test relatively simple hypotheses, through to complex three-dimensional numerical models which incorporate a broad range of processes within the atmosphere-geosphere-biosphere climate system (Figure 6). A major achievement in climate modelling over recent years has been the development of coupled models. These bring together atmospheric, oceanic, land-surface and sea-ice model components, and progressively others, into a single interacting global climate model.

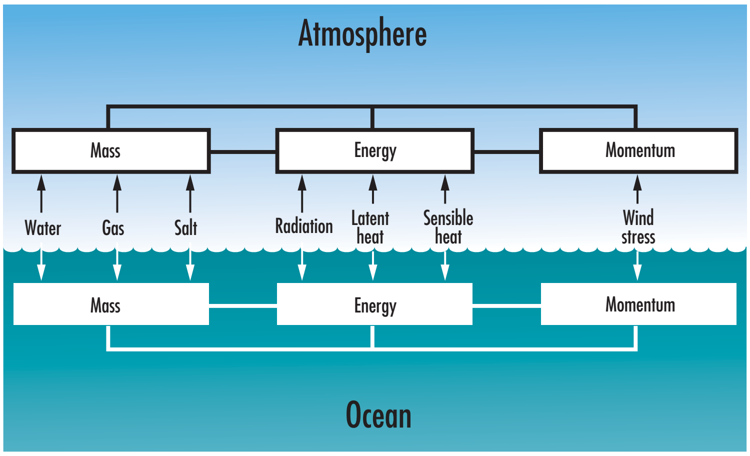


Figure 53. A schematic representation of the essential components of a fully coupled general circulation model, based on the conservation of mass, energy and momentum in the atmosphere and ocean, and the physical processes involved in the coupling between them.

General circulation models

A general circulation model (GCM) is a computer program which simulates the behaviour of the real atmosphere and/or ocean by incorporating our understanding of physical climate processes (Figures 6 to 9) into a set of mathematical equations which are used to calculate the future evolution of the system from some initial conditions. The key equations are those relating to the conservation of mass, momentum and energy in the atmosphere and ocean (Figure 53). The equations are solved at a large number of individual points on a three-dimensional grid covering the world (Figure 54) or by equivalent (e.g. spectral) methods.

The closeness of the points on the grid depends largely on the computing power available; in general, the more powerful the processor, the more detailed the achievable resolution of the model and the better the simulation. Typical calculations may have time steps of about half an hour over a global grid with resolution in the atmosphere of about 250 km in the horizontal and 1 km in the vertical. For the ocean component, spatial resolutions are typically 125-250 km in the horizontal and 200-400 m in the vertical. To make the numerical simulation process possible within the limits of present-day supercomputers, it is necessary to 'parameterise' the effects of short time and small space scale phenomena, such as individual clouds and storms.

Given the large thermal inertia of the ocean, the oceanic component of a coupled GCM may be 'spun up' over an extended period of time to allow it to reach a state close to equilibrium before coupling with the atmospheric component. In the real world, the ocean is probably never in equilibrium. Typically, the ocean GCM (OGCM) is spun up over 1000 model years (maybe 10,000 years for the deep ocean) while the atmospheric GCM (AGCM), together with the land-surface and sea-ice components, is typically run over five model years, prior to full coupling. Once coupled, the model is usually allowed to run for a few model decades to establish a control climate simulation, prior to interpretation of the results or further experimentation, such as altering the radiative forcing through increasing atmospheric carbon dioxide concentrations.

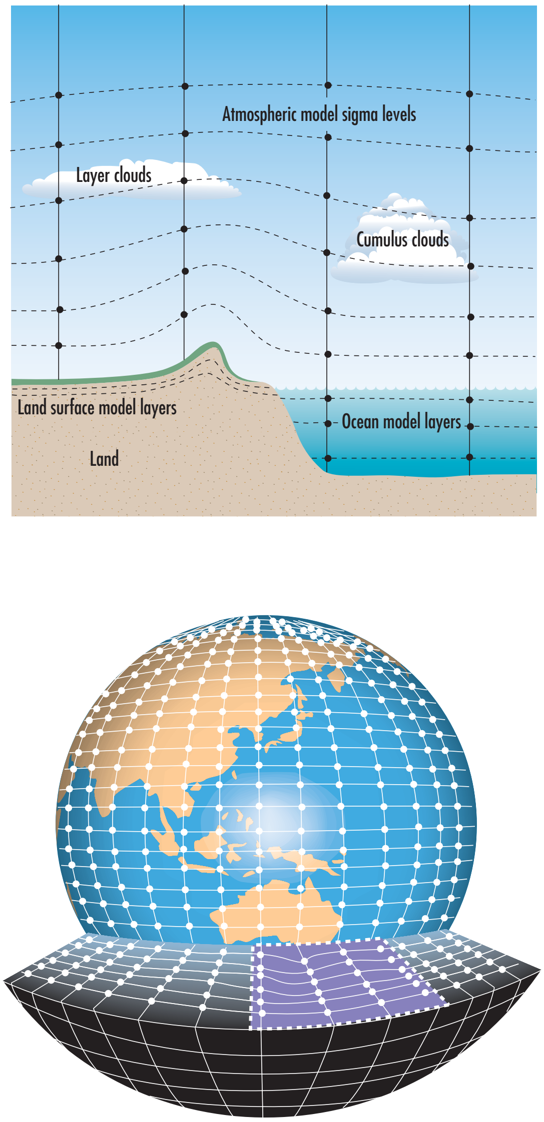


Figure 54. A schematic representation of the horizontal and vertical grid structure for a relatively coarse resolution general circulation model. The east-west cross-section in the top panel corresponds to the boxed area of the grid on the bottom and indicates the terrain following 'sigma levels' on which the numerical calculations are carried out. Because many important atmospheric phenomena (e.g. individual cumulus clouds) which influence the way the large-scale flow will develop are too small to be resolved by the computational grid, their effects are 'parameterised' in terms of the characteristics of the large-scale flow.

Many GCMs have been developed around the world for studies of seasonal to interannual predictability (El Niño time-scales), greenhouse forcing, nuclear winter and so on. Some of these have been derived directly from the operational global atmospheric models used for weather forecasting but extended for climate studies by coupling to appropriate models of the ocean, sea-ice and land-surface processes. Many have been purpose built for climate. The representation of the various physical processes and feedbacks differs from model to model. The sophistication of the modelling of the ocean ranges from so-called mixed layer models to incorporation of the complex three-dimensional deep-ocean circulation. There is also a broad spectrum in the treatment of the complexity of the land-surface component. In a few models, land and ocean carbon-cycle components have been included, as well as a sulphur-cycle component, representing the emissions of sulphur and their oxidisation to form aerosols. Atmospheric chemistry has largely been modelled outside the main climate model (i.e. off line), but recently it has been included in some models. Figure 55 illustrates how the various model components are first developed separately and then progressively coupled into comprehensive climate models.

Greenhouse climate simulations

Investigations of the potential human impact on the global climate are assisted by model simulations in which the concentrations of atmospheric greenhouse gases and aerosols are changed throughout the model simulation. Such studies have been carried out by over 30 modelling groups around the world since the late 1980s. The essential methodology of these studies is shown in Figure 57. A number of sequential steps are involved in developing a greenhouse climate model:

(a) The validation process (lower part of Figure 57) under which the equilibrium simulation of current climate with present-day greenhouse gas concentrations (1 x CO_2), is compared with the observed climate (A climate model reaches equilibrium when it becomes fully adjusted to its radiative forcing);

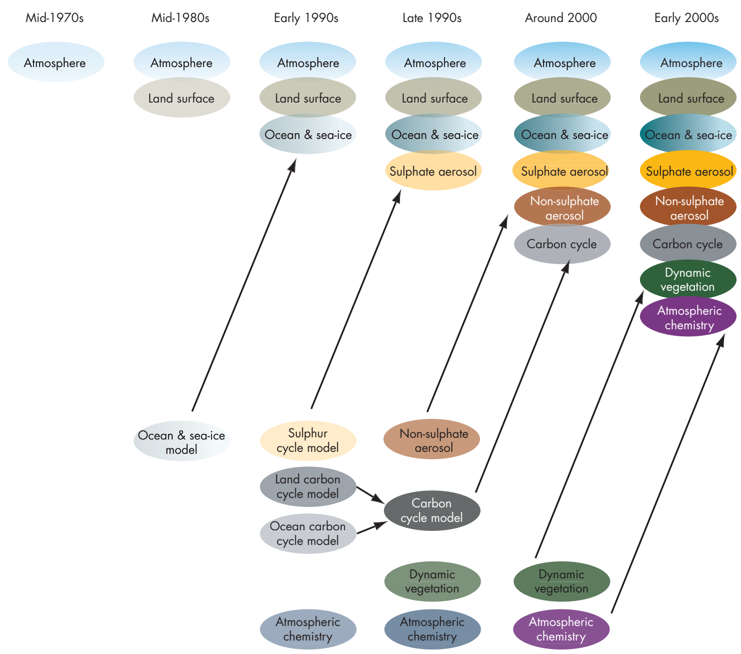


Figure 55. The development of climate models over the last 25 years, showing how the different components are first developed separately and later coupled into comprehensive climate models.

(b) An assessment of the change to the present climate, as computed by the model, that results from a similar model run using doubled carbon dioxide (2 x CO_2). The change, measured in terms of global mean temperature, between these two is usually referred to as the climate sensitivity of the model; and

(c) An assessment of the change to the model climate that results when CO_2 concentrations are increased gradually in the model, referred to as a transient experiment, in accordance with the greenhouse gas emission scenario that is adopted. The difference between the simulation of the present-day climate and the simulation at the time of CO_2 doubling in a 1% per year transient study, measured in terms of global mean temperature, is referred to as the transient climate response of the model.

The output of modelling studies is used to assess likely projected climate regimes under various greenhouse gas emission scenarios. Since the configurations and conditions governing individual coupled climate models can vary significantly, it is not unusual for the resulting projections to vary significantly, particularly at small space scales. Controlled experiments involving many models (so-called model intercomparisons), ideally in which the models are subjected to the same range of greenhouse forcing scenarios, can yield additional information about the characteristics of the individual models and a consensus view of the projected large-scale climate change.

Emission scenarios

Projections of climate change associated with human activities depend, among other things, on assumptions made about future emissions of greenhouse gases and tropospheric aerosols and the proportion of emissions that will remain in the atmosphere. To be plausible, these assumptions must take into account a range of realistic scenarios for the driving forces that will influence anthropogenic emissions, such as world population, economic growth, technological development and energy usage.

The relationship between emissions and atmospheric concentrations of greenhouse gases is important, since the concentrations are influenced not only by emissions of greenhouse gases, that is the sources, but also by the rate of removal of the gases from the atmosphere by 'carbon sinks'. While understanding of the detailed workings of the carbon cycle is still incomplete, many greenhouse gases have long lifetimes in the atmosphere. There is clear evidence that concentrations of CO_2 would continue rising for a substantial period after emissions were stabilised or even decreased. Refer to the box on the IPCC Special Report on Emission Scenarios (page 59).

Most climate models cannot be run over the full range of scenarios owing to both the complexity of computation and the processing time required to run transient coupled GCMs. A standard approach has been to run the models with a 1% per year

The modelling continuum – weather to climate

The question is often asked – how can we rely on climate model projections when we still cannot forecast weather accurately for even a week ahead? The question is particularly pertinent given that, in a number of cases, the same 'unified' numerical prediction model is used for both, with weather and climate models simulating the same physical and thermodynamic processes and solving the same mathematical equations but on different space and time-scales.

The apparent paradox is resolved by considering the nature of the predictions that we make for different periods ahead. Weather prediction involves forecasting the detailed behaviour of the atmosphere at specific times and locations. The precision that can be achieved tends to lessen as we consider times further into the future. For example, we may use a model to predict that a cool change will pass through Sydney at 4 pm tomorrow afternoon, but we cannot be as specific about a forecast of storms in the evening on the following day. The main reason for this limitation lies in the chaotic nature of the atmosphere. Small perturbations in the initial state of the atmosphere are amplified as the model (or real atmosphere) evolves into the future. This sensitivity limits the value of specific predictions of individual weather systems to about two weeks.

Time and space scales are also important determinants of how we can use models. Fluctuations in short-term models are driven by weather processes and their interaction with the land and ocean surface - the actual state of the atmosphere is what we seek to simulate, including the positions of highs and lows, effects of air mass movement over the surface, the wind flow, temperature, humidity and precipitation at a point and over an area. For long-term climate models, which yield projections about the average conditions or trends in average conditions, the more slowly varying components of the climate system, such as the ocean, exert a more dominant influence, with interactions and feedbacks between the ocean and the atmosphere and widespread changes in atmospheric composition providing a modifying effect.

For periods beyond about two weeks, we need to treat a forecast in terms of the average conditions prevailing over a period and region. And we can do so because these averages are governed by the same basic physics as governs the individual weather systems. We can thus reformulate our predictions in climate mode. For example, in some parts of the world we can give a useful outlook on the expected rainfall or temperature over the next three months. In these cases we are uncertain of the day-to-day or even week-to-week variations in weather, but we can demonstrate some skill in predicting the average behaviour over a season. Such seasonal outlooks are usually based on our understanding of the El Niño phenomenon which provides a large-scale control on the weather in many tropical and subtropical regions.

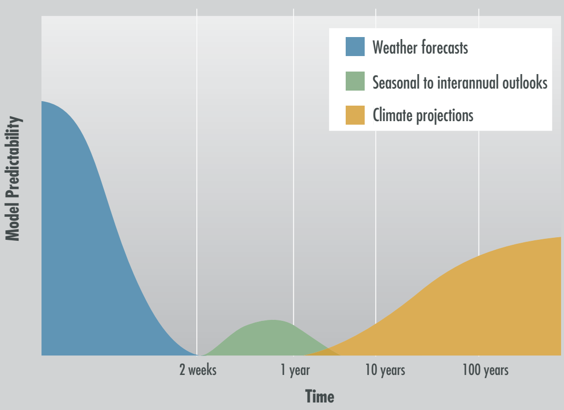


Figure 56. A schematic of the modelling continuum, demonstrating a level of model predictability on all time-scales. The nature of that information varies from detailed forecasts of weather systems to ensembles of seasonal to interannual outlooks to scenario-based projections of future climate averaged over relevant time and space scales.

When we generate longer-range climate projections under various greenhouse gas concentration scenarios, we need to recognise that, for each scenario, the model projections average over not only the day-to-day weather features like fronts and storms, but also large-scale features like the El Niño. A climate projection for 2100 is not seen to represent the actual weather to be encountered that year or even to represent whether there will be an El Niño event that year. Realistically the projection gives an estimate of the expected climate averaged over a period like a decade, recognising that there could be substantial variations from place to place and year to year due to particular events. Given the many influences likely to affect climate and weather on that time frame, this level of specificity is both relevant and appropriate (Figure 56).

The way models are run reflects both the time/space scales and the applications to which the results are put. For daily weather forecasts over eastern Australia, models are run at high resolution of around 30 to 50 km at the surface. For a climate projection 1000 years hence, it would be impossible, even with today's computer technology, to run the models at these resolutions. A typical climate model is run on a 250 km horizontal grid, and even at that resolution, requires weeks to months of computer time for a single run.

An important consequence of the space/time-scale differences is the resolution of the physical processes. The atmosphere, including its circulation and various physical processes, such as radiation, formation of clouds and precipitation, is a continuum. Even to characterise the circulation and capture the key processes in a high resolution weather forecasting model results in a loss of real information, with the model unable to capture the action happening at sub-grid scale. This is a critical aspect of the limits of predictability of a weather forecasting model, the chaos element. At climate time-scales, with the larger grid spacing, the amount of sub-grid scale action is much greater, and so the long time run of these models is, in fact, essential to integrate the behaviour of these processes and develop a picture of the circulation over time. In effect, at short times, close successive time steps and horizontal resolution enables us to take snapshots of the atmosphere which might be close to reality. On very long time-scales, the individual snapshots (on coarse time and space scales) may not be very meaningful but a series of snapshots can resolve the outlines, effects of the circulation, etc. In the middle, it is too coarse to resolve with individual shots and too short a record to integrate the effects. That is where ensembles of model runs are particularly important, with repeated runs over the same period providing an envelope of possible outcomes.

While the atmosphere is a true continuum that embraces all space and time-scales, we are unlikely to ever be capable of measuring or simulating it as a true continuum. We have learnt, however, to use numerical modelling tools to good effect to meet a range of weather and climate prediction challenges. And as the modelling tools, observing systems and underlying understanding become more sophisticated, we will hopefully get closer and closer to representing and simulating that continuum.

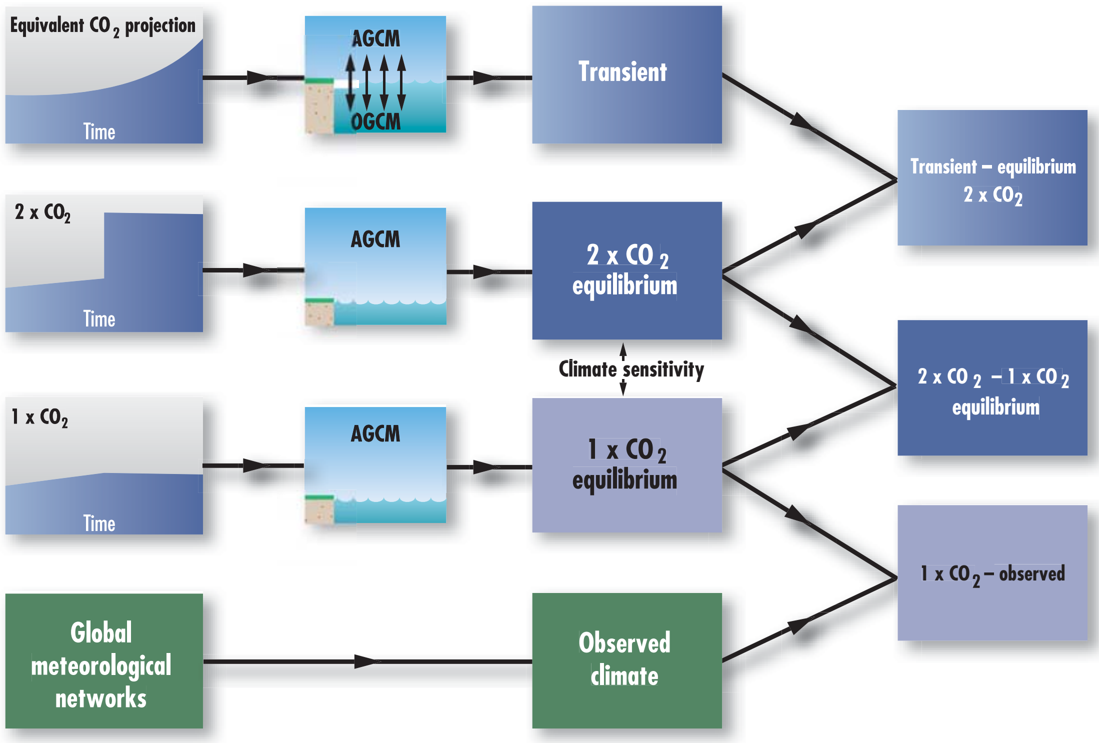


Figure 57. The methodology of greenhouse modelling. The validity of the climate model is first established by comparison of its simulation of the present-day (1 x CO_2) climate against the observed climate. The climate sensitivity of the model is then established by determining the difference in the global mean temperatures simulated by the model under present-day and under double present-day concentrations of carbon dioxide. Lastly the climate response of the coupled climate model to gradually increasing concentrations of carbon dioxide (a 'transient' experiment) is determined.

compound increase in CO_2 which is close to the current growth rate of the equivalent CO_2 (that is, including the equivalent effects of other greenhouse gases) concentration. Further exploration of the range of scenarios can then be achieved using simpler climate models, such as the energy balance - upwelling diffusion model.

Simple climate models

Comprehensive coupled GCMs are complex and require large computer resources to run. To explore all the possible greenhouse gas emission scenarios and the effects of assumptions or approximations in parameters in the model more thoroughly, simpler models are widely used and may be constructed to give similar results to the GCMs when globally averaged. Such models may involve simplified physical processes and dynamics, and coarser resolution. An example is the Energy Balance - Upwelling Diffusion Model (EB-UDM), also referred to as a box-upwelling diffusion model.

EB-UDMs are quite simple in concept and structure. The basic premise of the model is to represent the land and ocean areas in each hemisphere as individual 'boxes' with vertical diffusion (i.e. down-gradient mixing by eddies and turbulence) and upwelling (i.e. upward movement of water) to model heat transport within the ocean. Ocean waters are well-mixed within each hemisphere, with water sinking at the polar regions and rising towards the surface (upwelling) throughout the middle and tropical latitude regions.

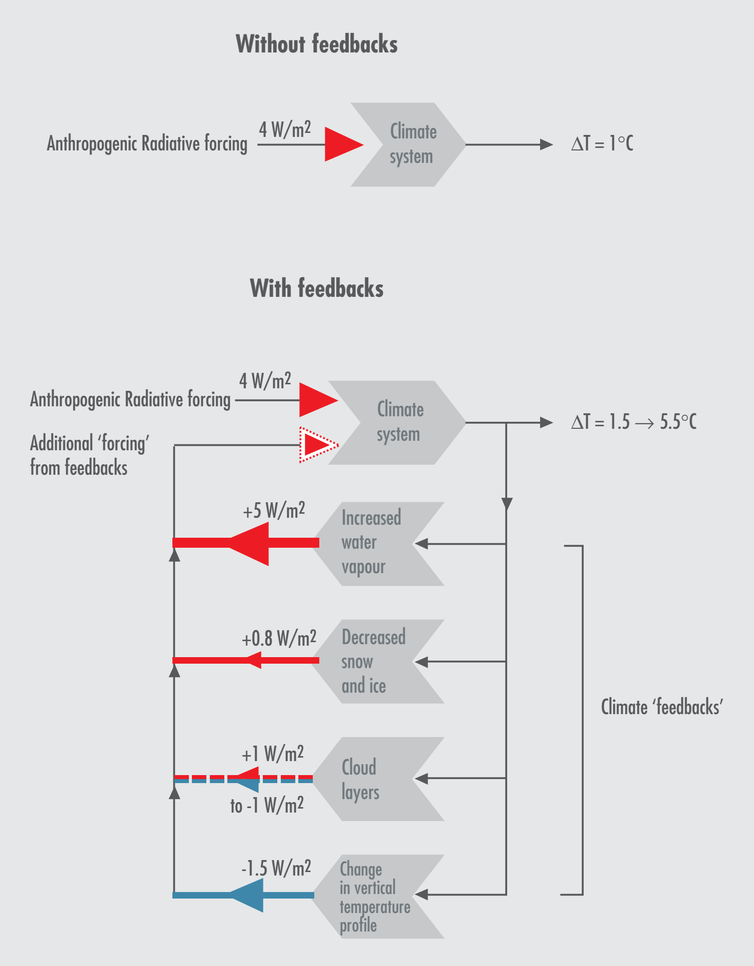


Figure 58. Schematic showing the influence of climate feedbacks on the amount and sign of radiative forcing driving a climate model. The arrows are indicative of the magnitude and sign of individual feedbacks, as determined from a Bureau of Meteorology Research Centre (BMRC) climate model. The dominant positive feedback is due to water vapour. In the BMRC model, cloud feedback is positive, but this varies greatly between models. The range in surface temperature changes indicated results from the varying effect of all feedbacks, but particularly of clouds.

By adjusting the structure and parameter values appropriately, EB-UDMs can be tuned to simulate the results of GCMs at the global-mean level. For example, the EB-UDM can be tuned to give the same response as a transient carbon dioxide experiment with a coupled GCM. Once a similar response has been achieved, further experiments can be conducted to simulate the response to varying climate sensitivities and to varying emission scenarios. Note that only global-mean values are derived from an EB-UDM, with no information as to spatial (horizontal or vertical) distributions.

Aerosols

Tropospheric aerosols play an important part in climate change studies. Their negative radiative forcing tends to counteract the positive forcing of increasing greenhouse gases to some extent. However, the relatively short lifetime of aerosols and their highly regionalised distribution (as illustrated in Figure 28) makes their inclusion in GCMs a complex matter. Various techniques are used, the simplest being to simulate their near-surface cooling effect by increasing the surface albedo on a regionally-varying basis. The inclusion of an interactive sulphur cycle to the model atmosphere allows the calculation of sulphate-aerosol concentration and its effect on the climate, both directly through scattering of solar radiation and indirectly through changing cloud properties. More recently, it has been possible to include the effects of other important aerosols, such as mineral dust, sea salt and biomass smoke.

Climate model feedbacks

Much of the uncertainty in output from climate models is caused by limitations in the understanding of feedback mechanisms within the climate system. These can act to amplify a modelled climate response (positive feedback) or counteract it (negative feedback) (Figure 58). Recent developments in offline diagnostic techniques allow individual feedback mechanisms within GCMs to be investigated. This allows the effect on outgoing long wave and incoming short wave radiation, and the strength of the feedback at different heights and locations, to be determined. Sub-components of the major feedbacks, such as clouds, may also be examined (e.g. height, amount, optical properties). Greater understanding of climate model feedbacks will help quantify the role of critical physical processes in determining the overall response to changes in climate model forcing.

Water vapour is an extremely complex greenhouse gas. With its ability to undergo phase changes and form clouds in all their rich variety, water vapour presents a challenge to scientists, both to understand and to model. The amount of water vapour the atmosphere can hold increases rapidly with temperature and thus increases in temperature tend to be associated with increases in water vapour. Because water vapour is a powerful greenhouse gas, this leads to more warming, resulting in a positive feedback.

Clouds act to 'trap' outgoing long wave radiation, resulting in additional surface warming. But at the same time, clouds are bright and reflect solar radiation back to space, which acts to cool the surface. The net feedback effect depends on changes to cloud amount, cloud height, thickness and radiative properties, which in turn depend on the distribution of water droplets, ice particles and aerosols within the cloud. Typically, increases in the fraction of bright low clouds acts to cool the surface, while more deep high-topped clouds act to warm the surface. Because of the great complexity of this feedback, the net effect of clouds on the global climate remains unclear. Current climate models display a wide spread in sign and magnitude of the overall cloud feedback.

Another major feedback of the climate system relates to changes in ice and snow cover. Sea-ice reflects more incoming solar radiation to space than the sea surface. Consequently the reduction of sea ice associated with greenhouse warming leads to a positive feedback at high latitudes. Similarly, snow has greater reflectivity than the land surface so a reduction in snow cover also leads to positive feedback. Other important feedbacks relate to changes in the atmospheric temperature lapse rate (i.e. the temperature change with height) and, in the longer term, changes in the land surface.

Model validation and intercomparison

If GCMs are to provide reliable projections of future climate, the models must be capable of accurately simulating the present-day climate and some of the reasonably well-documented climates of the past, based on the known external controls, such as incoming solar radiation, distribution of continents and oceans, atmospheric composition and so on.

A common method of validation is a comparison between a model-simulated element, such as annual mean precipitation, and the observed climatological pattern. Figure 59 illustrates such a comparison for global precipitation, demonstrating that the Bureau

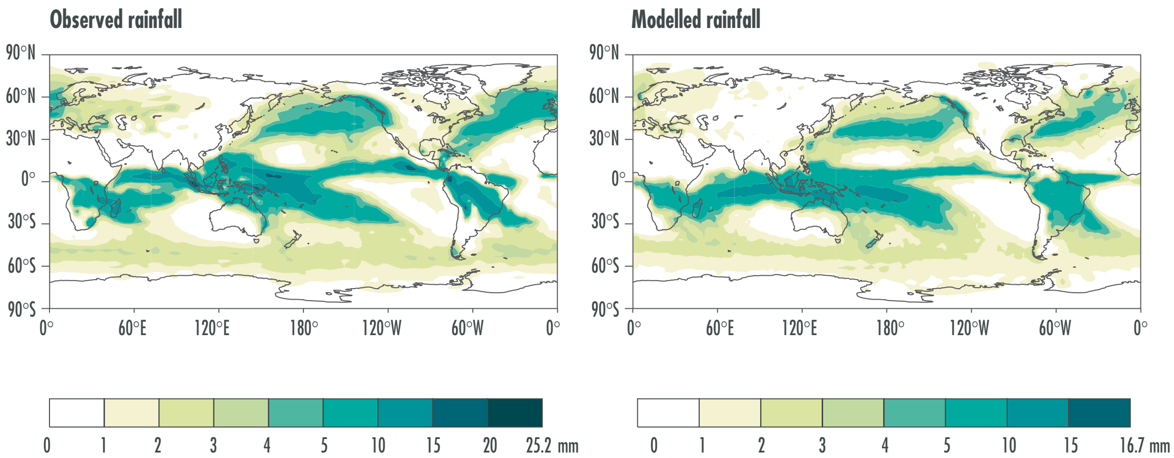


Figure 59. Comparison between (left) the observed climatological pattern of global precipitation and (right) the simulated pattern produced by the BMRC climate model.

of Meteorology Research Centre (BMRC) climate model is capable of realistically simulating the observed climatological pattern. Models must also be validated for climate variability as well as means. This is an important process in the challenging task of detecting and measuring trends or changes in climate that may be due to forcing factors other than internal, natural fluctuations in climate.

While validation against present climate provides an indication of the broad accuracy of models, intercomparison with other models provides an indication of the level of confidence in such models. By subjecting a range of models, with varying formulations, to an agreed set of parameters (boundary conditions, future forcing scenarios etc.), the results of the models can be compared. The relative strengths of models in different areas (e.g. cloud processes, radiative forcing, etc.) can be assessed, as well as providing a consensus view of model projections. It should be noted, however, that agreement between models does not guarantee that the results are correct.

Modelling a greenhouse-warmed world

The time evolution of global-mean surface temperature in a transient carbon dioxide experiment using a flux-adjusted BMRC coupled general circulation model is shown in Figure 60. CO_2 concentration is increased from the control level (330 ppmv) by 1% compound per year, from model year 29 until ten years after the concentration has doubled. At the time of CO_2 doubling, the warming effect of the increased CO_2 is given by the temperature difference between the control and transient experiments, some 1.3°C in this case.

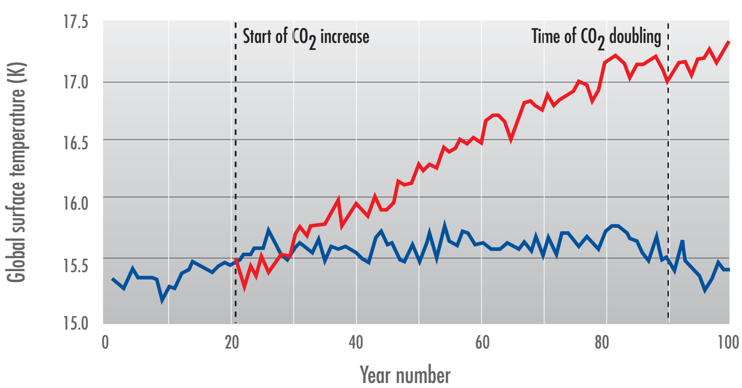


Figure 60. Global-mean surface temperature variation with time using the fully-coupled BMRC climate model. The transient run, with CO_2 increasing at 1% per year from year number 29, is compared with a control (1 x CO_2 (330 ppmv)) run.

Considerable spatial variation exists in modelled changes in climate. Consequently, it is important to investigate the geographical patterns of climate change over the globe. Figure 61 shows the distribution of annual mean warming as predicted by a BMRC model at the time of CO_2 doubling. The strongest warming is evident over the northern landmasses and the polar regions. Figure 62 shows the distribution of changes in the annual mean precipitation at the time of carbon dioxide doubling using the same model, with increased precipitation strongest over the tropics.

The thermal response through the depth of the atmosphere and ocean to increased carbon dioxide, is illustrated by a zonal cross-section of mean atmospheric and oceanic temperature changes at the time of doubling (Figure 63). It is apparent that warming penetrates to great depth in the ocean at high northern and southern latitudes.

Model projections of El Niño-Southern Oscillation

The El Niño-Southern Oscillation phenomena are a dominant influence on the climate in many parts of the globe, including Australia. It is therefore important to understand the potential changes in El Niño associated with global warming. Many climate models show an El Niño-like response to enhanced greenhouse forcing, with sea-surface temperatures of the central and eastern tropical Pacific generally projected to warm faster than those of the western tropical Pacific. However, the potential ramifications of this are not fully understood. The physical processes that enable El Niño events to develop and decay are still the subject of active research, and global climate models often have difficulty representing the magnitude, duration and seasonal phase of El Niño events. Consequently, projections of changes in the frequency, amplitude and pattern of El Niño events should be treated with caution. Some current projections indicate little change in El Niño events over the next century (Figure 64). However, even with little or no change in the amplitude and frequency of El Niño events, the impacts of these events could be exacerbated by long-term trends associated with global warming, such as an intensification of the hydrological cycle.

Regional climate modelling

When it comes to assessing the potential impacts of climate change on countries and communities, it is necessary to look beyond the global-mean estimates and global-scale distributions of climate variables to the regional scale (sub-continental) and local scale (typically 50 to 100 km² areas). For any change in the large-scale circulation, changes at both local and regional scales may differ significantly from place to place. This is due to interactions with local topographic features, such as coastlines and mountains, as well as to the greater natural variability experienced on smaller scales. Furthermore, the relatively coarse grids used to run large-scale models are limited in their ability to capture accurately the range of climate processes and feedbacks that act at the smaller scales.

Various techniques can be applied to derive regional-scale climate projections from global-scale models, including:

- using GCMs at finer horizontal resolution. This is computationally very expensive and only limited simulation times can be supported (e.g. 5 to 10 years), leaving the results statistically uncertain;
- statistical 'downscaling', which relates local surface climate variables, such as rainfall or temperature, to larger-scale predictors determined by the GCMs; and
- use of fine resolution local area models (LAMs), driven at their lateral boundaries by the time-dependent output of coupled atmosphere-ocean GCMs. As a rule, LAMs perform better outside the tropics and in finer resolution GCMs, but they are inherently limited by the regional-scale flow patterns of the driving GCM. With complementary local topography, LAMs give far more realistic local detail of surface climate features than GCMs.

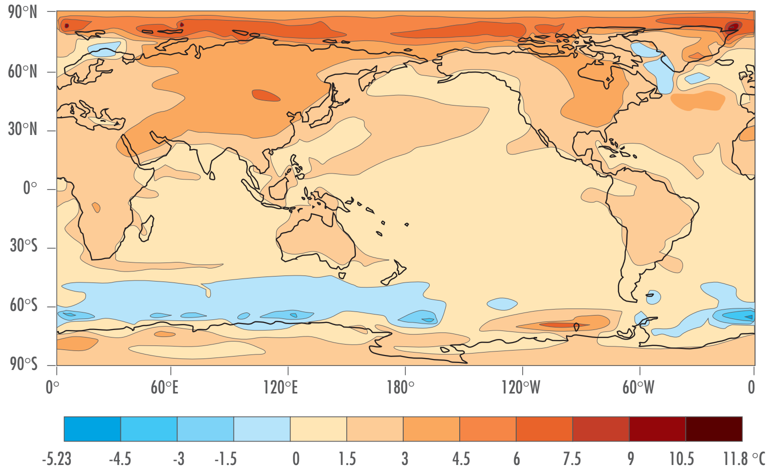


Figure 61. The distribution of annual mean warming (transient - control) given as a 20-year mean centred on the time of CO_2 doubling, from a transient CO_2 experiment with the BMRC coupled climate model.

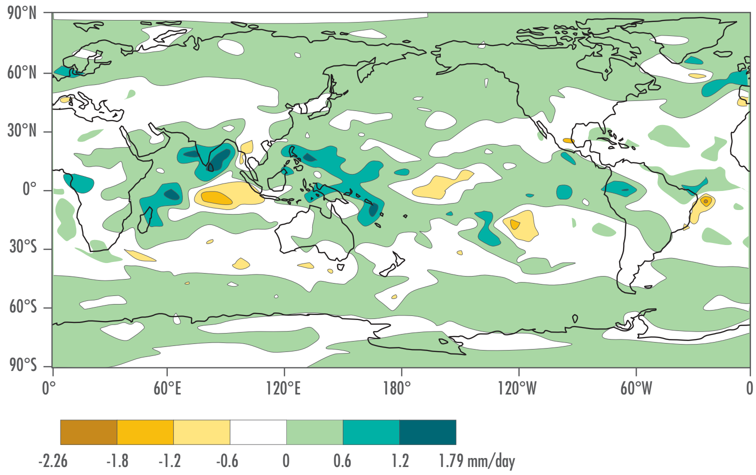


Figure 62. The distribution of change in annual mean precipitation (transient – control) given as a 20-year mean centred on the time of CO_2 doubling, from a transient CO_2 experiment with the BMRC coupled climate model.

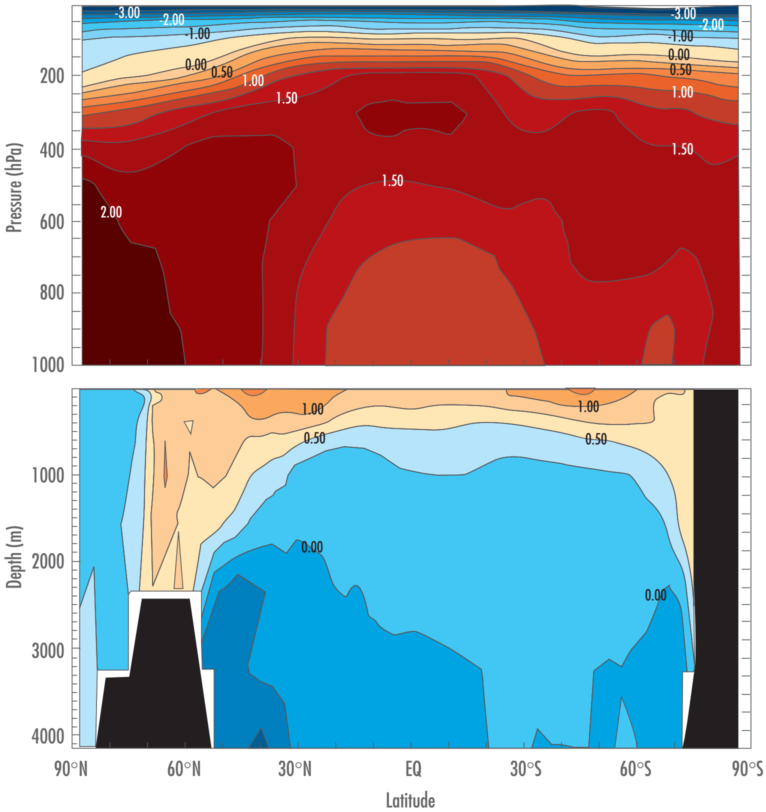


Figure 63. A zonal cross-section of temperature changes (transient - control) at the time of doubling in the BMRC coupled climate model. The vertical profile extends from an ocean depth of 4000 m to the surface (OGCM) and from the near surface (1000 hPa level) to the highest modelled level of the atmosphere, above 10 hPa (AGCM).

Large differences in regional-model climate projections produced to date suggest a low level of confidence in their reliability for producing realistic climate projections. Improvements in regional model performance, however, should be realised in line with improved GCMs, increased computing power and better understanding of climate feedback processes. In the meantime, the results are useful as the basis of regional climate sensitivity studies.

Statistical downscaling

Statistical models can be used to downscale the coarse grid output from GCMs to the finer resolutions required to investigate the regional and environmental impacts of climate change (Figure 65). This involves using observational data to establish statistical relationships between local climate variables and broadscale atmospheric variables, such as mean sea-level pressure (MSLP) and geopotential height, for which GCM output is considered reliable. These relationships are then used to infer local variables from the GCM output at a high temporal resolution, such as daily. Hence, projected changes in extreme events can be investigated.

However, these methods are limited to regions where long records of surface climate observations are available over a relatively dense network, such as southeastern Australia and southwest Western Australia. Locally observed weather information, such as daily extremes of temperature and rainfall, are typically used, but other variables relevant for climate impact studies may be included. A long, high-quality data record is needed and the local variables must be driven by large-scale atmospheric forcing in order to enable a successful statistical relationship to be built. The list of these impact-related variables is theoretically endless and frequently studied examples include Growing Degree-Day (GDD), river flow and crop yield. An important index of agricultural production, GDD is an integrated measure of temperature based on the amount of time in a day that the temperature is between particular thresholds important for plant growth. As such it is directly forced by the synoptic situation.

The very low computational cost of the statistical model enables its application to several large-scale model scenarios. An added benefit is the ability to assess the uncertainties associated with climate change projections, a very important element of impact studies. The Bureau of Meteorology Research Centre has examined projected changes in various parameters, including GDD, using the downscaling approach and compared projected climate changes with direct GCM projections, finding good general agreement but noting that local differences near significant mountain features can be important.

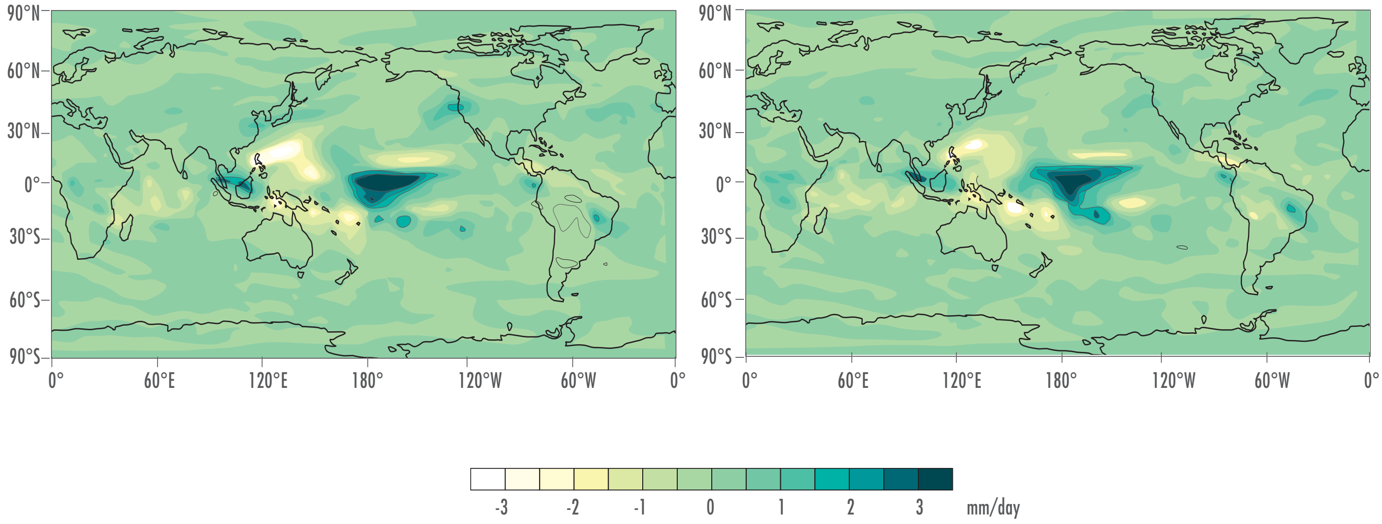


Figure 64. Mean December-February rainfall anomalies (mm/day) during El Niño events, in (left) control and (right) transient simulations of a BMRC climate model. The similarity between the rainfall anomaly patterns in this model suggests that greenhouse warming will result in little change to the mean patterns of rainfall anomaly associated with El Niño events.

Looking for a greenhouse signal

The signal of any human-induced effect on climate will be superimposed on the background noise of natural climate variability resulting from both internal fluctuations and external causes, as described earlier. In order to understand the full implications of climate change, significant effort has been devoted to distinguishing between anthropogenic and natural influences. This process involves demonstrating that an observed change in climate is highly unusual in a statistical sense and then attributing the change to a particular cause.

Considerable progress has been achieved in attempts to separate the natural and anthropogenic signatures in the climate record. Most recently, the effects of solar variations and volcanic aerosols in addition to greenhouse gases and sulphate aerosols have been included, thus leading to more realistic estimates of human-induced radiative forcing. These have been used in climate models to provide more complete simulations of the human-induced climate change 'signal'. Simulations with coupled ocean-atmosphere models have provided important

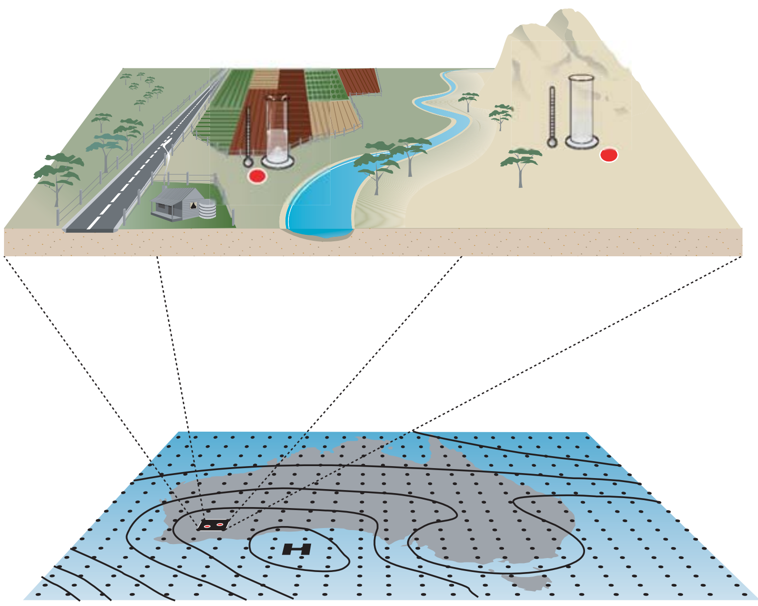


Figure 65. A schematic diagram describing the statistical downscaling approach. GCMs provide useful predictions for large-scale atmospheric patterns (lower part). Details contained within a grid box (upper part) are influenced by local features beyond the resolution of current global climate models.

information about decade to century natural internal variability. Another major area of effort involves comparison between modelled and observed spatial and temporal patterns of climate change.

Pattern-based studies have also been useful in comparing the modelled response to combined forcing by greenhouse gases and anthropogenic sulphate aerosols with observed geographic, seasonal and vertical patterns of atmospheric temperature change. These studies show that such pattern similarities increase with time as the anthropogenic signal increases in strength. The probability is very low that these similarities could occur by chance as a result of natural internal variability only.

Future model improvements

Notwithstanding the enormous advances that have been made since the mid 1980s, the scope for further improvements in climate models is large. In the coming years, major efforts will aim to:

- Achieve a more complete understanding of dominant climate processes and feedbacks, particularly clouds and their effects on radiation and role in the hydrological cycle. These are considered the greatest source of uncertainty in models due to both positive and negative climate feedback mechanisms. Efforts are focusing on the introduction of cloud microphysics into atmospheric GCMs, as well as improved understanding of cloud dynamics.
- Improve the simulation of deep ocean circulation in GCMs, including the thermohaline circulation. This will rely on sustained ocean observing programs, such as those of the Global Ocean Observing System.
- Perform long-term climate simulations, for comparison with ice-core data and to determine the patterns of long-term climate variability.
- Improve the modelling of sea-ice and land surface processes.
- Explore the probabilities of future climate projections by developing ensembles of greenhouse climate simulations.
- Progress downscaling techniques to improve the regional climate modelling required to determine local impacts and possible shifts in extreme weather events.

Other areas in which model improvements will be achieved include global carbon cycle models, methods of computing radiative fluxes and the treatment of tropospheric chemistry.

International development of the climate issue

Serious concern at the prospect of irreversible changes to climate as a result of human activities began to surface in the scientific community in the 1950s and was founded on two closely linked considerations:

- the expectation that the burning of fossil fuels since the Industrial Revolution would eventually lead to significant build-up of carbon dioxide in the atmosphere; and
- simple physical arguments which suggested that the greater the concentration of carbon dioxide in the atmosphere, the greater the surface warming.

The issue increasingly attracted the attention of governments and led to an enhanced focus on observations of carbon dioxide, in particular the establishment of the Mauna Loa monitoring station (Figure 25) in 1957. Within a decade, it became clear that there was a steady upward trend in carbon dioxide concentration superimposed on, but additional to, a marked annual cycle. Evidence from ice cores and other sources soon confirmed that this steady rise in carbon dioxide concentration had already been going on for a long time.

The 1970s witnessed a period of vigorous scientific debate on climate change. Triggered by speculation, partly based on extrapolation of the northern hemisphere cooling trend since the 1940s, many thought that the earth was about to descend into a new ice age. However, by the end of the decade, increasingly sophisticated models of the general circulation reinforced the prospect of global warming and the focus of scientific concern with respect to long-term climate change returned to the enhanced greenhouse effect. Some early calculations on the cooling effect of aerosols also contributed to the debate.

The (First) World Climate Conference (FWCC) was convened by the World Meteorological Organization (WMO) in February 1979 to examine the climate issue. The Declaration issued at the conclusion of the Conference read:

'Having regard to the all-pervading influence of climate on human society and on many fields of human activity and endeavour, the Conference finds that it is now urgently necessary for the nations of the world:

(a) To take full advantage of man's present knowledge of climate;

(b) To take steps to improve significantly that knowledge;

(c) To foresee and to prevent potential man-made changes in climate that might be adverse to the well-being of humanity.'

The recommendations of the FWCC triggered the establishment of extensive internationally-coordinated scientific efforts to monitor, understand and predict climate and climate change. In particular, following the appeal issued by the FWCC, the Eighth World Meteorological Congress formally established the World Climate Programme as a major international, interagency and interdisciplinary effort to, among other things, provide the means of foreseeing future possible changes in climate. The following two decades witnessed a complex interplay of issues and events linking climate with the emerging global agenda for sustainable development (Figure 66). Key among them was the 1985 Villach Conference, which brought together scientists from 29 countries in an assessment of the role of carbon dioxide and other greenhouse gases in climate variations and associated impacts.

An extensive international array of organisations and processes now exist, through which nations are attempting to achieve coordinated global action on the climate change issue. More importantly, systematic linkages have been established between the major UN system organisations dealing with climate change, from the monitoring and research carried out under the World Climate Programme and related monitoring and research programs, through to the scientific, technical and socio-economic assessment work of the IPCC, to the political negotiations of the Framework Convention on Climate Change (FCCC).

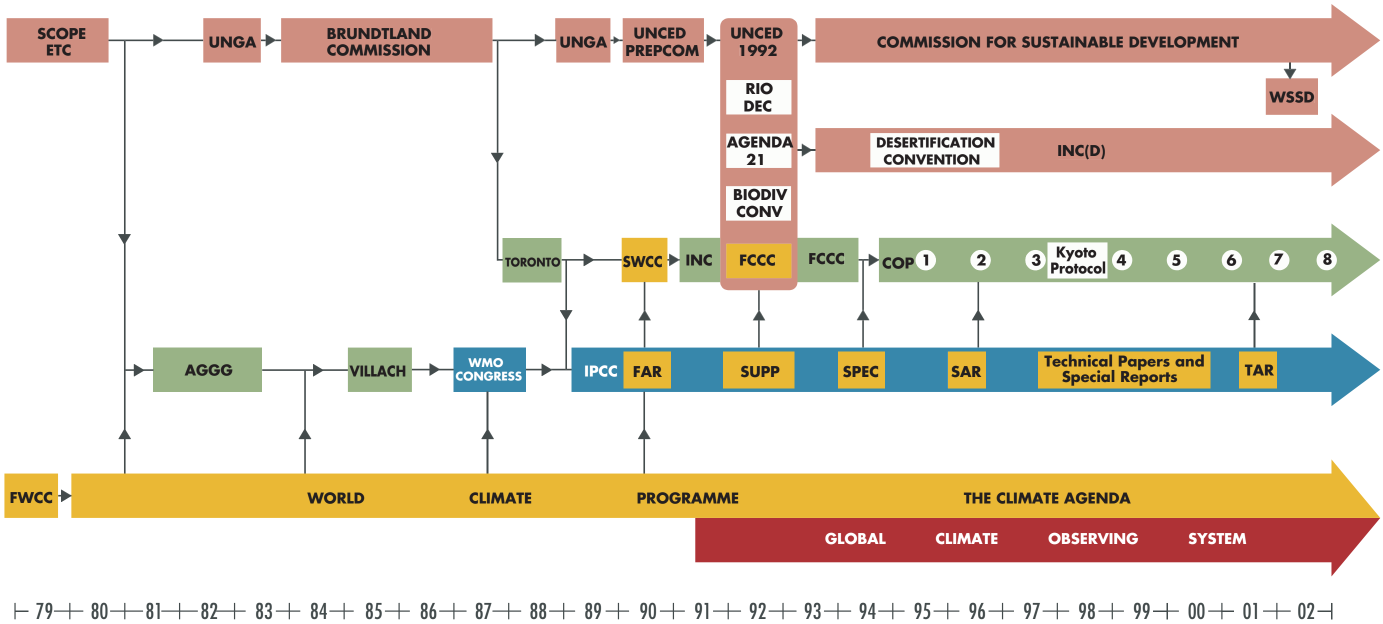


Figure 66. Some of the major influences and events in the international development of the climate issue from the time of the First World Climate Conference (FWCC) and the establishment of the World Climate Programme (WCP) by the World Meteorological Organization (WMO) Eighth Congress in 1979 through to the Eighth Session of the Conference of the Parties to the Framework Convention on Climate Change (COP FCCC) in October-November 2002. Following the 1985 Villach Conference, the WMO Tenth Congress authorised the establishment of the joint WMO-UNEP (United Nations Environment Programme) Intergovernmental Panel on Climate Change (IPCC), whose First Assessment Report (FAR) to the 1990 Second World Climate Conference (SWCC) led to the establishment of the Intergovernmental Negotiating Committee (INC) for a Framework Convention on Climate Change (FCCC). This emerged as a centrepiece of the 1992 United Nations Conference on Environment and Development (UNCED) which had itself been convened by the United Nations General Assembly (UNGA) in response to the report of the UNGA-sponsored Brundtland Commission. The Villach Conference and the 1988 Toronto Conference on the Changing Atmosphere provided two of the major links between the development of the climate change issue and the broader international agenda for sustainable development now proceeding under the auspices of the Commission for Sustainable Development (CSD). The Second Assessment Report (SAR) of the IPCC was a key consideration of the FCCC in the negotiating period leading to the adoption of the Kyoto Protocol at COP3 in 1997. The IPCC's Third Assessment Report (TAR) contributed to finalisation of the Marrakech Accords at COP7 in 2001 and to the ongoing implementation of the Convention (refer to box on FCCC, p.52). For remaining acronyms, refer to 'Acronyms and abbreviations'.

Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988, under the joint sponsorship of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), in response to the growing concern and uncertainty amongst governments about the prospect and implications of human-induced global climate change. Its mandate was to carry out an internationally coordinated assessment of the magnitude, impact and possible response strategies for climate change. The inaugural Chairman of the IPCC was Professor Bert Bolin of Sweden.

The IPCC is a scientific and technical assessment body with the primary task of providing broadly-based expert assessments of the state of knowledge of the climate change issue based on research and investigations carried out under the World Climate Programme (WCP) and other relevant international and national programs. It is not itself a research-performing organisation and, while its mandate includes the assessment of policy options, it does not engage in policy formulation or political negotiation which are the responsibility of other bodies such as the Conference of the Parties to the Framework Convention on Climate Change (FCCC). The relationship between the IPCC, the climate research and monitoring communities, the intergovernmental climate policy process of the UN and, in particular, the FCCC is illustrated schematically in Figure 67.

The structure of the IPCC and its range of assessments has evolved since its establishment in response to the changing needs and priorities of the policy community and to address the requirements for specific methodological work. Recognising the

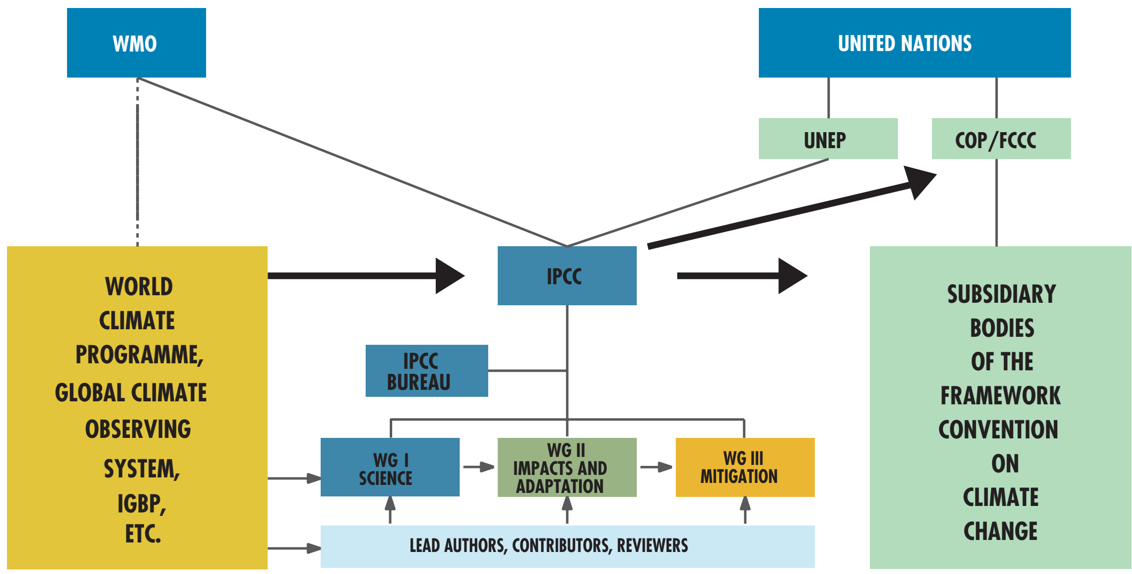


Figure 67. The World Climate Programme, through its monitoring, applications and research activities, the associated Global Climate Observing System (GCOS) and other research programs, such as the International Geosphere-Biosphere Programme (IGBP), provide the scientific basis for the assessment work of the Intergovernmental Panel on Climate Change (IPCC) and its three Working Groups (WG) as input to the political negotiation processes under the Conference of the Parties (COP) to the Framework Convention on Climate Change (FCCC). The specific responsibilities of the three IPCC Working Groups have evolved since their establishment and are shown here according to their most recent (2002) assignments.

full breadth of the scientific, technical and socio-economic aspects of climate change, three Working Groups (WG) were set up to provide assessment of the state of the science (WGI), the potential impacts of climate change (WGII) and possible response strategies (WGIII).

The IPCC's First Assessment Report was approved in August 1990 and provided the main scientific basis for the Ministerial Declaration of the Second World Climate Conference and the subsequent establishment of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (INC/FCCC). A Supplementary Report was completed in February 1992, as input to the final negotiating session of the INC/FCCC in May 1992.

Following the June 1992 signing of the Framework Convention on Climate Change (see box on p.52), the IPCC was restructured in November 1992 with revised terms of reference. The responsibilities of the three Working Groups were redefined as follows:

- WGI - assessment of science relevant to climate change (as for the First Assessment Report);
- WGII - assessment of impacts and response options (essentially a merger of the former WGII and WGIII); and
- WGIII - cross-cutting economic and other issues.

The work program of the restructured IPCC through 1993-95 focused on two main tasks:

- preparation of a 1994 Special Report for the First Session of the Conference of the Parties (COP1) to the FCCC, covering a number of key topics of particular relevance at the early stage of implementing the Convention; and
- preparation of a comprehensive Second Assessment Report (SAR), which was completed in 1995.

The SAR was a principal input to COP2 in Geneva in July 1996, in the lead up to negotiation and adoption of the Kyoto Protocol at COP3 in December 1997. The SAR was considered in detail by the subsidiary bodies to the FCCC, in particular, the Subsidiary Body on Scientific and Technological Advice (SBSTA) and the Ad hoc Group on the Berlin Mandate (AGBM). An important element of the SAR was the Synthesis Report, which integrated and synthesised material from all three Working Group reports. The SBSTA and AGBM requested further expansion and clarification of several issues, which lead to the preparation, through 1996-97, of a number of Technical Papers aimed at addressing these issues on the basis of the full material (i.e. the Summaries for Policymakers and the underlying Working Group reports) from the Second Assessment Report.

With a now-ongoing requirement by governments and by the FCCC for up-to-date assessments of the climate change issue, the IPCC commenced preparation in late 1996 of a Third Assessment Report (TAR). Dr Robert Watson of the USA was elected Chairman of the IPCC for the TAR and the Working Group responsibilities were redefined as:

- WGI – science: assessment of the scientific aspects of the climate system and climate change (as for the SAR);
- WGII – impacts and adaptation: assessment of the vulnerability of ecological systems, socio-economic sectors and human health to climate change and the potential consequences, with an emphasis on regional and cross-sectoral issues; and
- WGIII – mitigation: assessment of the mitigation of climate change and the methodological aspects of cross-cutting issues.

The climate change issue cannot, of course, be neatly divided into three parts. As illustrated in Figure 68, there is a continual feedback loop between the climate we are likely to experience, the real and projected impacts and the mitigation strategies we put in place. This feedback cycle is an intrinsic part of the IPCC assessment philosophy and its approach to climate modelling.

A dedicated Task Force on National Greenhouse Gas Inventories was established in 1998 to take over the inventory work that had been jointly managed by the IPCC Working Group I, the Organisation for Economic Cooperation and Development (OECD) and the International Energy Agency (IEA). The establishment of the Task Force recognised the increased focus on land use, land use change and forestry sectors that emerged through the FCCC Kyoto Protocol process.

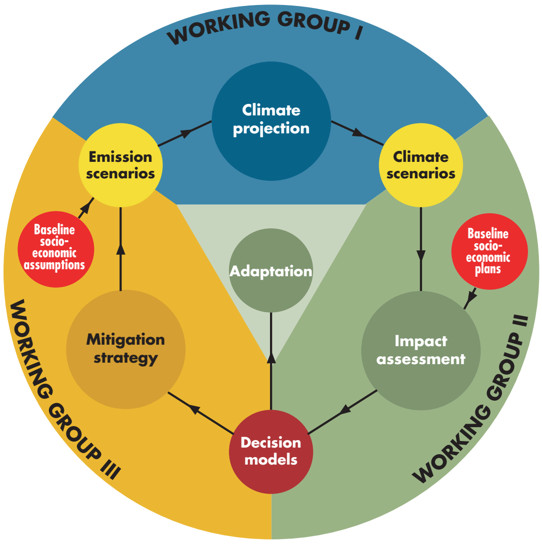


Figure 68. The IPCC Working Groups span the breadth of issues associated with understanding and responding to climate change, and recognise the feedbacks and flow-on effects in terms of both information and actions. This is inherent in the IPCC methodology for using greenhouse gas emission scenarios as input to biogeochemical and physical climate models to produce projections of alternative climate futures. In turn these are used in impact sensitivity studies as an aid to decision-making on the optimum balance between the complementary strategies of mitigation and adaptation.

In parallel with the conduct of the TAR, a series of Special Reports was initiated to respond to specific assessment needs indicated by the SBSTA and, in the case of the aviation report, by the International Civil Aviation Organization (ICAO):

- Special Report on Aviation and the Global Atmosphere, approved in April 1999;
- Special Report on Emissions Scenarios (SRES) (March 2000);
- Special Report on Methodological and Technological Issues in Technology Transfer (SRTT) (March 2000); and
- Special Report on Land Use, Land Use Change and Forestry (SRLUCF) (May 2000).

Following the completion of the TAR in 2001, the IPCC immediately addressed the overall framework for the conduct of the Fourth Assessment Report, which it decided would be completed during 2007. As is IPCC practice, a new Bureau was elected to guide the IPCC through the upcoming assessment cycle, under the chairmanship of Dr Rajendra Pachauri of India, continuing the same Working Group and Task Force structure, albeit with new co-chair responsibilities (Figure 69) and a greater focus on cross-cutting issues.

A strength of the IPCC process, and fundamental to its success, is its fully transparent review and approval procedures. These are clearly enunciated

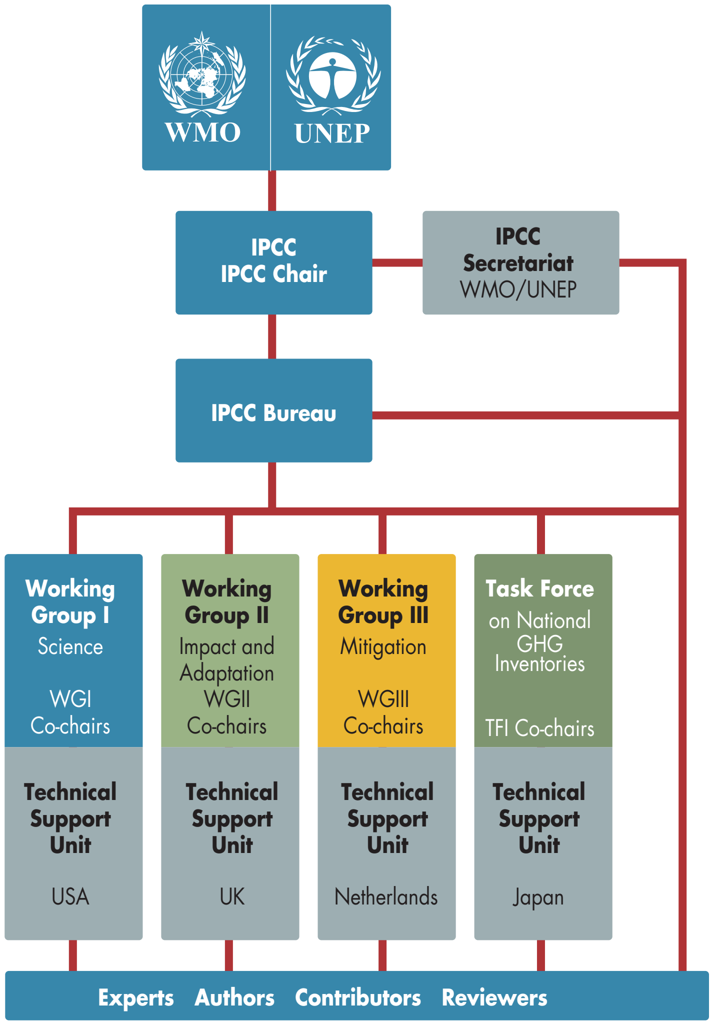


Figure 69. The structure of the IPCC for the conduct of the Fourth Assessment Report, including the host countries for the Technical Support Units, which are supported by the country of the developed country co-chairs.

The United Nations Framework Convention on Climate Change

In the 1980s, increasing scientific evidence that human activities had been contributing to substantial increases in atmospheric greenhouse gas concentrations led to growing international concern about the possibility of global climate change. In response, the 45th session of the United Nations General Assembly in 1990 adopted a resolution that established the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (INC/FCCC) to prepare an effective convention. The United Nations Framework Convention on Climate Change (UN FCCC) was adopted on 9 May 1992 and opened for signature at the UN Conference on Environment and Development in June 1992 in Rio de Janeiro, where it received 155 signatures. The convention entered into force on 21 March 1994, 90 days after receipt of the 50th ratification. As of January 2003, it has been ratified by 187 countries.

Article 2 of the Convention expresses its ultimate objective:

> '... stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.'

At its first session in Berlin (March - April 1995), the Conference of the Parties to the UN FCCC (COP1) reached agreement on what many believed to be the central issue before it, the adequacy of commitments (the Berlin Mandate). The COP1 also reached agreement on other important issues, including the establishment of the subsidiary bodies, which included the Subsidiary Body for Scientific and Technological Advice (SBSTA). The task of the SBSTA is to link scientific, technical and technological assessments, together with information provided by competent international bodies, to the policy-oriented needs of the COP.

The early efforts of the FCCC and its subsidiary bodies culminated at COP3 in Kyoto (December 1997) with the adoption of the Kyoto Protocol. COP3 also initiated an enhanced focus and work program on climate science and, in particular, on the adequacy of global observing systems for climate. The IPCC and the GCOS play key roles in facilitating this program, in collaboration with the international climate science community.

As well as continuing to advance the full implementation of the Convention, subsequent sessions focussed on negotiating the rules and principles that are necessary to enable ratification and entry into force of the Kyoto Protocol, including adoption of the Buenos Aires Plan of Action (COP4, October – November 1998) and its finalisation through the Marrakech Accords at COP7, October-November 2001.

The bodies of the FCCC, especially the SBSTA, work closely with the IPCC and draw heavily on the assessments of the IPCC to fulfil their functions. The IPCC Second and Third Assessment Reports, as well as the many specially commissioned Special Reports, have provided the principal scientific input to discussions and negotiations of the Convention bodies and inform their deliberations on an ongoing basis.

in the agreed IPCC guidelines for the preparation of reports, and specify requirements for stringent expert and government review processes. The guidelines also spell out the role of the Review Editors, whose task is to oversee the review process and ensure that government and expert review comments are considered fairly and that controversial views are represented adequately in the Working Group reports.

Australia has actively participated in the work of the IPCC from the outset. This includes lead and contributing author roles in the preparation of reports, the organisation and funding of expert meetings and workshops, peer and country reviews of draft reports, national representation at the sessions of both the Panel and its Working Groups and representation in various capacities on the IPCC Bureau.

IPCC Third Assessment Report

The IPCC Third Assessment Report (TAR) was finalised and approved during 2001. The magnitude of the effort involved in the IPCC process is illustrated in Figure 70, which maps out the many sessions of the IPCC, its Bureau and its Working Groups that were convened from the completion of the Second Assessment Report (SAR) through the preparation and finalisation of the TAR.

The three Working Group reports that make up the main part of the TAR, were approved at sessions of the respective Working Groups, as follows:

- WGI report (Climate Change 2001. The Scientific Basis) at the eighth session of WGI in Shanghai in January 2001;
- WGII report (Climate Change 2001. Impacts, Adaptation and Vulnerability) at the sixth session of WGII in Geneva in February 2001; and

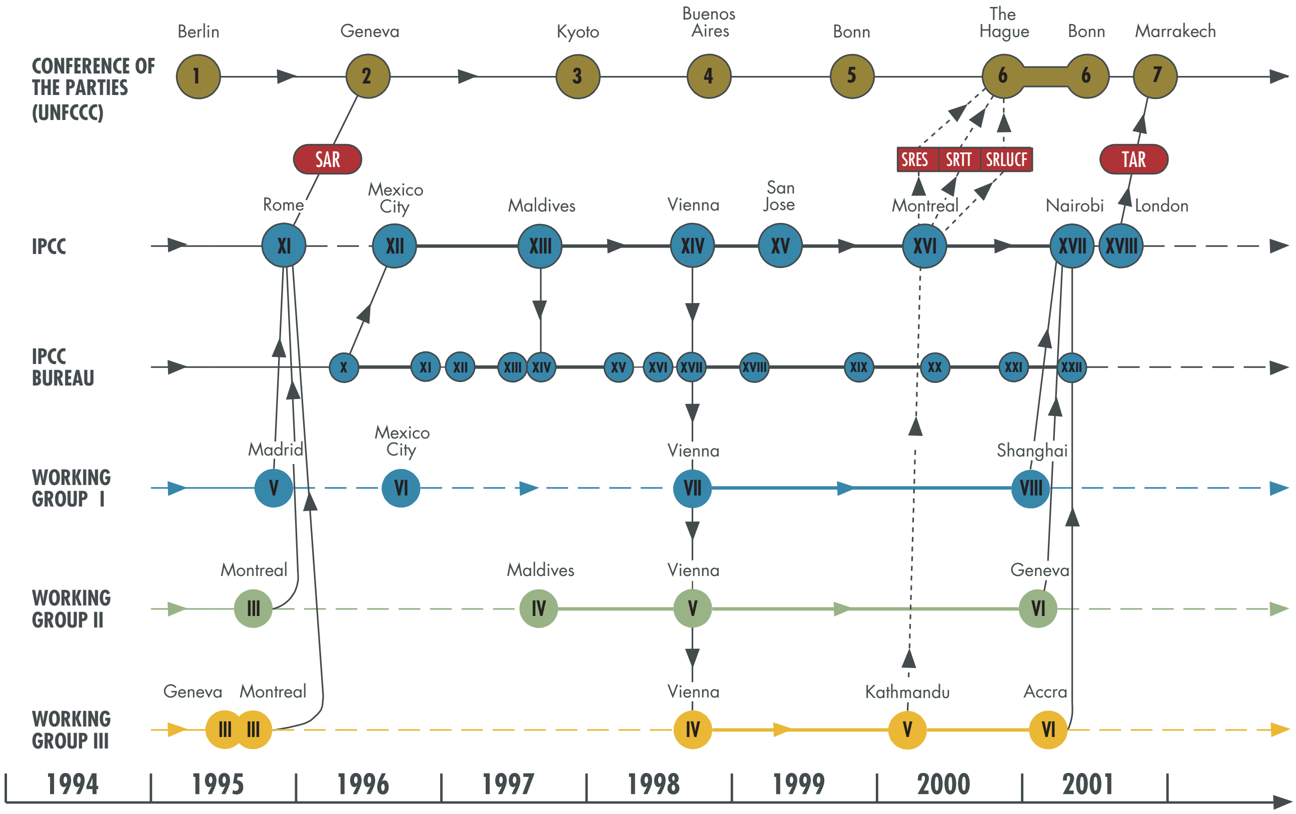


Figure 70. The IPCC process for the preparation of the Third Assessment Report (TAR), including the Special Reports on Emissions Scenarios (SRES), Technology Transfer (SRTT) and Land Use Change and Forestry (SRLUCF), and the various sessions of the Conference of the Parties to which the reports were submitted.

- WGIII report (Climate Change 2001. Mitigation) at the sixth session of WGIII in Accra, Ghana, in March 2001.

The final component of the four volume TAR (Figure 71), the Synthesis Report, was completed at the eighteenth session of the IPCC in London in September 2001 with the Summary for Policymakers (SPM) approved on a line-by-line basis and formal adoption of the underlying full report. The Synthesis Report drew together information from the other three volumes and relevant Special Reports to respond to specific policy-relevant questions posed by the SBSTA.

The Third Assessment Report of the IPCC is, until the release of its successor, the most comprehensive and authoritative statement of current knowledge on all aspects of climate change. Arguably, the most important finding, particularly in the context of the FCCC, was that 'most of the warming observed over the last 50 years is attributable to human activities'. As well as identifying the consensus view on many relevant subjects, the report also highlights the areas where uncertainties remain and further effort is required.

The key findings of the three Working Group reports may be summarised as follows.

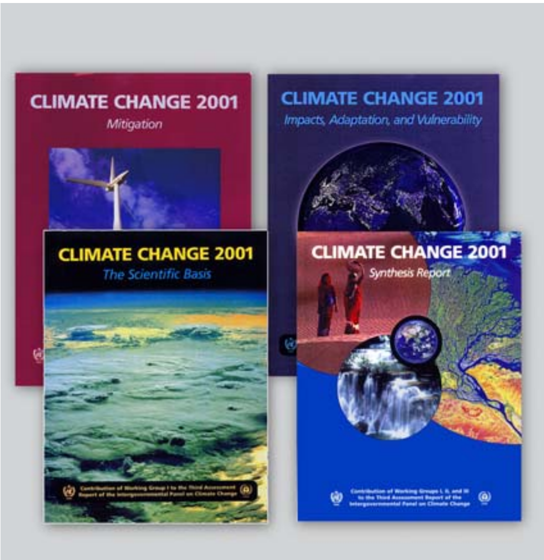


Figure 71. The four volumes that together make up the Third Assessment Report of the IPCC.

Climate change science (Working Group I)

A useful summary of the key findings of the assessment of climate change science is given by the section headings used in the Working Group I Summary for Policymakers:

- An increasing body of observations gives a collective picture of a warming world and other changes in the climate system;
- Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate;
- Confidence in the ability of models to project future climate has increased;
- There is new and stronger evidence that most of the warming over the last 50 years is attributable to human activities;
- Human influences will continue to change atmospheric composition throughout the 21st century;
- Global average temperature and sea level are projected to rise under all IPCC SRES scenarios;
- Anthropogenic climate change will persist for many centuries; and
- Further action is required to address remaining gaps in information and understanding.

A more comprehensive, but still considerably simplified, summary of the findings on climate change science is given in the next major section.

Impacts and adaptation (Working Group II)

The main messages in the Summary for Policymakers of the Working Group II report have been summarised by the Working Group as:

- Recent regional climate changes, particularly temperature increases, have already affected many physical and biological systems;
- There are preliminary indications that some human systems have been affected by recent increases in floods and droughts;
- Natural systems are vulnerable to climate change, and some will be irreversibly damaged;
- Many human systems are sensitive to climate change and some are vulnerable;

- Projected changes in climate extremes could have major consequences;
- The potential for large-scale and possibly irreversible impacts poses risks that have yet to be reliably quantified;
- Adaptation is a necessary strategy at all scales to complement climate change mitigation efforts;
- Those with the least resources have the least capacity to adapt and are the most vulnerable; and
- Adaptation, sustainable development and enhancement of equity can be mutually reinforcing.

Figure 72. IPCC Working Group I meet to discuss the approval of the Third Assessment Report.

Mitigation (Working Group III)

The Working Group III report does not lend itself to as succinct a summary as those of the other reports, but the key findings include:

- Climate change is intimately linked to broader development issues;
- Equity concerns arise within and between countries and generations;
- Climate-friendly energy sources are developing rapidly and are the key to cutting emissions;
- Many low-emissions technologies are available but are not being fully exploited;
- All sectors can pursue energy conservation and efficiency improvements;
- Industry's main short-term option is to enhance energy efficiency and many options exist for moving to cleaner energy sources;
- Enhancing carbon sinks can partially offset fossil fuel emissions and improved agricultural management can boost carbon storage;
- Behavioural and economic changes can support technological options;
- Mitigation policies can have both costs and benefits, with costs depending on the assumptions made;
- Internationally traded emissions allowances could lower costs;
- Developed country mitigation policies could affect developing country economies;
- Action to reduce energy emissions can have social and economic implications, with mixed effects on industry;
- Mitigation policies can improve land-use practices;
- There are many barriers to the diffusion of climate-friendly technologies including institutional, cultural, economic and technological barriers;
- Many different policies and measures can help overcome barriers and countries may benefit from coordinating their policies and measures;
- Non-climate policies can also affect greenhouse gas emissions, and there are strong interlinkages between environment and development issues;
- National policies can ensure that climate change and sustainable development goals are mutually reinforcing; and
- Synergies can be captured through institutional changes and stakeholder involvement.

The findings of the Third Assessment Report (TAR) in respect of the scientific basis of climate change as set down in the fourteen chapters of the report are summarised for the scientific readership in the Technical Summary and for the non-scientific readership in the Summary for Policymakers (SPM). While it is important to stress that, because of its method of preparation and approval, the SPM, in particular, must be read as a whole in order to gain what the IPCC Working Group I community have agreed is a balanced overview of current understanding and uncertainties, the following paragraphs attempt to further summarise the main findings in a more succinct form.

Observed changes in the climate system

Since the finalisation of the SAR in 1995, additional data from new studies of current and past climates, improved analysis of data sets, more rigorous evaluation of quality and comparisons among data from different sources, have led to greater confidence in the description of past changes of climate. Some of the key conclusions of the TAR are that:

- the global average surface temperature has increased over the twentieth century by about 0.6°C (with a 95 per cent confidence range of ±0.2°C);
- temperatures have risen during the past four decades in the lowest eight kilometres of the atmosphere;
- snow cover and ice extent have decreased;
- global average sea level has risen and ocean heat content has increased;
- changes have also occurred in other important aspects of climate; but also that
- some important aspects of climate appear not to have changed.

The TAR includes a very large amount of information in its Chapter 2 from which it is concluded that an increasing body of observations gives a collective picture of a warming world and other changes in the climate system.

Forcing agents that cause climate change

As described more fully earlier, changes in climate occur as a result of both internal variability within the climate system and external factors (both natural and anthropogenic). The influence of external factors on climate can be broadly compared using the concept of radiative forcing, with a positive radiative forcing, such as that produced by increasing concentrations of greenhouse gases, tending to warm the surface. A negative radiative forcing, which can arise from an increase in some types of aerosols tends to cool the surface. The TAR provides a range of data and analyses which demonstrate, in summary, that:

- concentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities;
- anthropogenic aerosols are short-lived and mostly produce negative radiative forcing; and
- natural factors, such as changes in solar output or volcanoes, have made small contributions over the past century.

This has led to the overall conclusion that emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect climate.

Simulation of the climate system and its changes

Complex climate models are required to provide detailed estimates of feedbacks and of regional features. Such models cannot yet simulate all aspects of climate and there are particular uncertainties associated with clouds and their interaction with radiation and aerosols. Nevertheless, confidence in the ability of these models to provide useful projections of future climate has improved due to their demonstrated performance on a range of space and time-scales. In particular:

- understanding of climate processes and their incorporation in climate models has improved, including water vapour, sea-ice dynamics and ocean heat transport;

- some recent models produce satisfactory simulations of current climate without the need for the non-physical adjustments of heat and water fluxes at the ocean-atmosphere interface used in earlier models;
- simulations that include estimates of natural and anthropogenic forcing reproduce the observed large-scale changes in surface temperature over the 20th century; and
- some aspects of model simulations of the El Niño–Southern Ocean phenomena (ENSO), monsoons and the North Atlantic Oscillation, as well as selected periods of past climate, have improved.

In summary, the TAR concludes that confidence in the ability of models to project future climate has increased.

Identification of human influence on climate change

The Second Assessment Report (SAR) concluded: 'The balance of evidence suggests a discernible human influence on global climate'. That report also noted that the anthropogenic signal was still emerging from the background of natural climate variability. Since the SAR, progress has been made in reducing uncertainty, particularly with respect to distinguishing and quantifying the magnitude of responses to different external influences. Although many of the sources of uncertainty identified in the SAR still remain to a degree, new evidence and improved understanding support an updated conclusion. In particular, the TAR concluded that:

- there is a longer and more closely scrutinised temperature record and new model estimates of variability;
- there are new estimates of the climate response to natural and anthropogenic forcing, and new detection techniques have been applied;
- simulations of the response to natural forcings alone do not explain the warming in the second half of the twentieth century;
- the warming over the past 50 years due to anthropogenic greenhouse gases can be identified despite uncertainties in forcing due to anthropogenic sulphate aerosol and natural factors;
- detection and attribution studies comparing model simulated changes with the observed record can now take into account uncertainty in the magnitude of the modelled response to external forcing;
- most of these studies find that, over the past 50 years, the estimated rate and magnitude of warming due to increasing concentrations of greenhouse gases alone are comparable with, or larger than, the observed warming; and
- the best agreement between model simulations

Why IPCC projects, not predicts, future climate

The distinction between projections and predictions is extremely important in that the climate projections are dependent, among other things, on the assumptions that are made in respect of the future emissions of greenhouse gases and other forcing agents. Since there is no way of determining what these will be (they will depend on future human actions) it is impossible, even with the best climate models, to actually predict the future climate.

and observations over the past 140 years has been found when all the above anthropogenic and natural forcing factors are combined (Figure 73).

The summary conclusion is that there is new and stronger evidence that most of the warming observed over the past fifty years is attributable to human activities. The Working Group agreed, in particular, that:

- in the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations;
- it is very likely that the twentieth century warming has contributed significantly to the observed sea-level rise, through thermal expansion of sea water and widespread loss of land ice.

Projections of the earth's future climate

The IPCC methodology for producing what it refers to as 'projections' (not predictions – see box on p.57) of future global climate is largely as described earlier, in the section on Climate Modelling. In summary, it involves the following steps:

- adoption of a set of emissions scenarios for the various greenhouse gases and aerosols corresponding to a range of plausible demographic, technological and other trends through the 21st century (see box on IPCC SRES on p.59);
- use of carbon cycle and chemistry models to convert the emissions scenarios into concentration scenarios;
- use of the concentration scenarios to determine the radiative forcing as input to sophisticated global climate models which are run out for a hundred years or more to determine modelled patterns of climate change and, among other things, the climate sensitivity of the model, i.e. the global mean warming that the model produces for doubled carbon dioxide;
- use of the climate sensitivity to calibrate simple global mean models which can be run more quickly and cheaply with a larger range of scenarios to give globally averaged warming trends over a century or more.

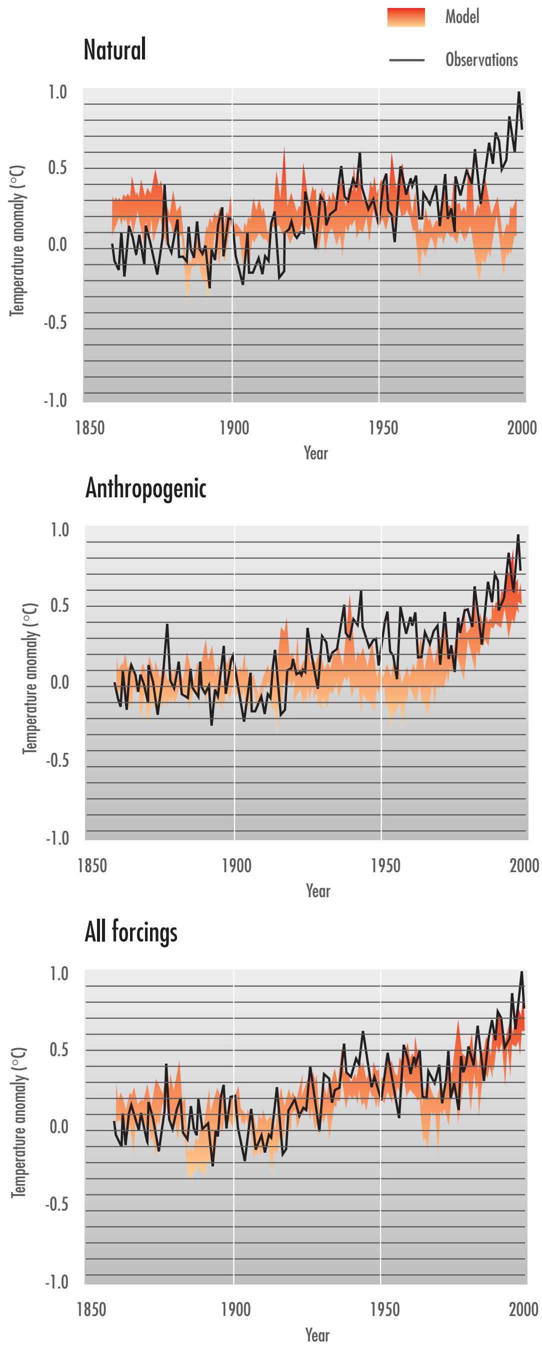


Figure 73. Observed global surface temperature anomalies compared to model simulations with (top) natural, (middle) anthropogenic and (bottom) both natural and anthropogenic forcing mechanisms.

IPCC Special Report on Emissions Scenarios (SRES)

In order to understand how global climate could change over the next hundred years, it is necessary for climate models to represent in some way information on possible changes in greenhouse gas emissions over that time period. Such information, on theoretical paths for growth in greenhouse gas emissions over time, is necessarily based on a wide range of considerations related to the future development of human societies, such as population changes, economic development, technological change, energy supply and demand, and land use change.

In September 1996, the IPCC initiated an 'open process' approach for the development of new emissions scenarios, involving input and feedback from a broad community of experts, culminating in approval of a Special Report on Emissions Scenarios (SRES) by the IPCC Working Group III in Kathmandu in March 2000. The scenarios are firmly based on published and peer reviewed literature, and represent the state-of-the-art at the time of preparation of the SRES.

The SRES scenarios are characterised on the basis of four 'storylines' (Figure 74), which are based on sets of assumptions about possible alternative futures. Each storyline yields a family of scenarios, totalling 40 altogether, with each considered equally sound. The future worlds described by the four storylines are:

A1: a world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Three A1 groups are defined with specific technological emphases: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

A2: a very heterogeneous world, featuring self-reliance, preservation of local identities, continuously increasing population and economic development which is primarily regionally oriented.

B1: a convergent world with the same global population as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies.

B2: a world which emphasises local solutions to economic, social and environmental sustainability, with continuously increasing global population, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines.

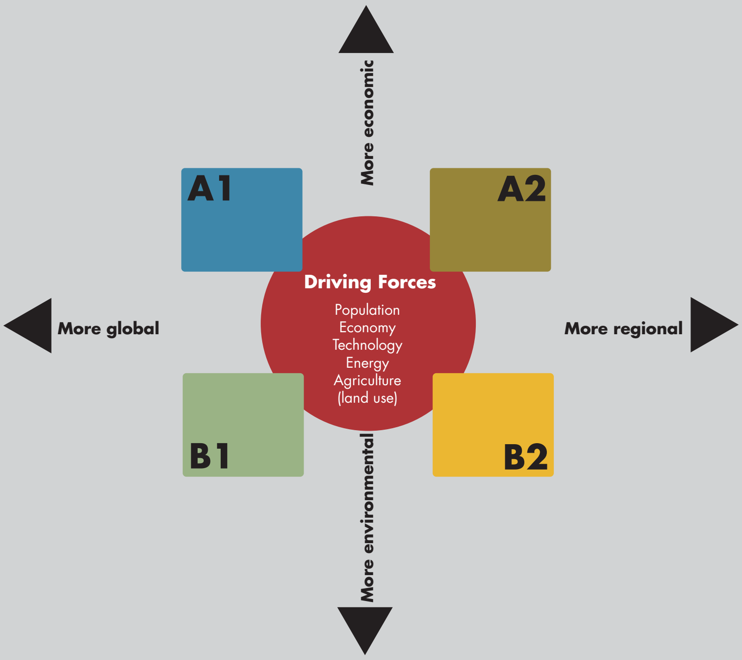


Figure 74. Schematic diagram of the SRES scenarios, illustrating the main driving forces of greenhouse gas emissions and characterising the scenarios in terms of the four storylines or scenario families. Each storyline assumes a distinctly different direction for future developments, such that the four storylines differ in increasingly irreversible ways.

A substantially simplified representation of the results presented in the TAR is given in Figure 75. Clockwise from the lower left hand corner, Figure 75 shows the range of emission scenarios for just one gas, carbon dioxide, and (top left) the resulting modelled concentrations, highlighting the A1FI and B1 scenarios along with the most commonly quoted of an earlier batch of IPCC scenarios, the so-called IS92a scenario (see box on IPCC SRES, p.59). The right-hand side shows the resulting temperature (top) and sea-level rise (lower) patterns which are indicative also of the range of uncertainty introduced by the range of climate sensitivity values employed (1.7°C to 4.2°C with an ensemble mean of 2.8°C, compared with an assumed range of 1.5°C to 4.5°C and a mean of 2.5°C for both the FAR and the SAR).

On the basis of its adoption of the SRES scenarios and its review of the broader greenhouse gas and aerosol science, the TAR concluded that human influences will continue to change atmospheric composition throughout the 21st century.

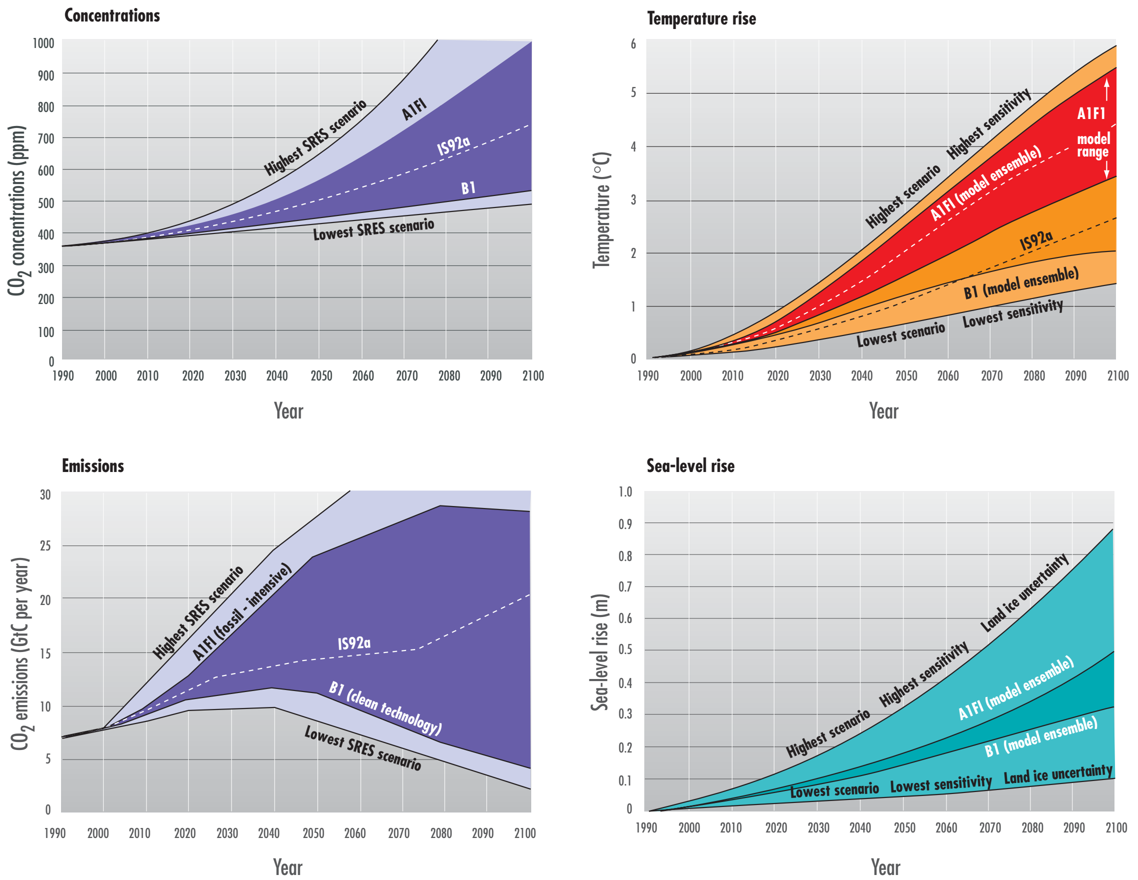


Figure 75. Using a wide range of climate models, the IPCC TAR demonstrated the projected response of the climate system to various scenarios of greenhouse gas and other human-induced emissions. Clockwise from lower left (a) the range of IPCC carbon dioxide emissions scenarios from the IPCC Special Report on Emissions Scenarios (SRES), noting in particular the A1FI (Fossil Intensive) and B1 (clean technology) 'marker' scenarios and, for reference, one of the 1992 IPCC scenarios, IS92a; (b) the carbon dioxide concentrations that would result from the IPCC carbon dioxide emissions scenarios as shown in (a); (c) projected global mean surface temperature changes from 1990 to 2100 for the full set of SRES emissions scenarios, illustrating, for example, the range of model projections derived using the A1F1 emissions; and (d) projected global mean sea-level changes from 1990 to 2100 for the full set of SRES emissions scenarios as well as for the A1F1 and B1 scenarios in particular.

On the basis of calculations of temperature and sea-level rise, using both coupled atmosphere-ocean general circulation models and simple models tuned to the more complex general circulation models, the TAR indicates, among other things, that:

- the globally averaged surface temperature is projected to rise by 1.4°C to 5.8°C over the period 1990 to 2100 for the full range of SRES emissions scenarios and the full range of climate sensitivities (1.7°C to 4.2°C) of the general circulation models used in the TAR;
- temperature increases are projected to be greater than those given in the SAR (which were in the range 1.0°C to 3.5°C for the six IS92 scenarios), due primarily to the lower projected sulphur dioxide emissions in the SRES scenarios;
- the projected temperature rise is likely to be greater than any seen in the last 1000 years (Figure 76);
- land areas will warm more than the global average;
- it is very likely that, during the twenty-first century, the earth will experience:
  - higher maximum temperatures and more hot days over nearly all land areas;
  - higher minimum temperatures, fewer cold days and fewer frost days over nearly all land areas;
  - reduced diurnal temperature range over most land areas;
  - more intense precipitation events over many areas; and
- global mean sea level is projected to rise by 0.09 to 0.88 metres between 1990 and 2100 for the full range of SRES scenarios.

The TAR reports, in summary, that global average temperature and sea level are projected to rise under all IPCC SRES scenarios. The report also points out that:

- emissions of long-lived greenhouse gases have a lasting effect on atmospheric composition, radiative forcing and climate;
- after greenhouse gas concentrations have stabilised, global average surface temperatures would rise at a rate of only a few tenths of a degree per century rather than several degrees per century as projected for the twentieth century without stabilisation;
- global mean surface temperature increases and rising sea level from thermal expansion of the ocean are projected to continue for hundreds of years after stabilisation of greenhouse gas concentrations;
- ice sheets will continue to react to climate warming and contribute to sea-level rise for thousands of years after climate has been stabilised;
- current ice dynamic models suggest that the West Antarctic ice sheet could contribute up to 3 metres to sea-level rise over the next 1000 years, but such results are strongly dependent on model assumptions; and
- given the non-linear nature of the climate system, future climate change may involve surprises, such as rapid circulation changes in the North Atlantic;

and concludes that anthropogenic climate change will persist for many centuries.

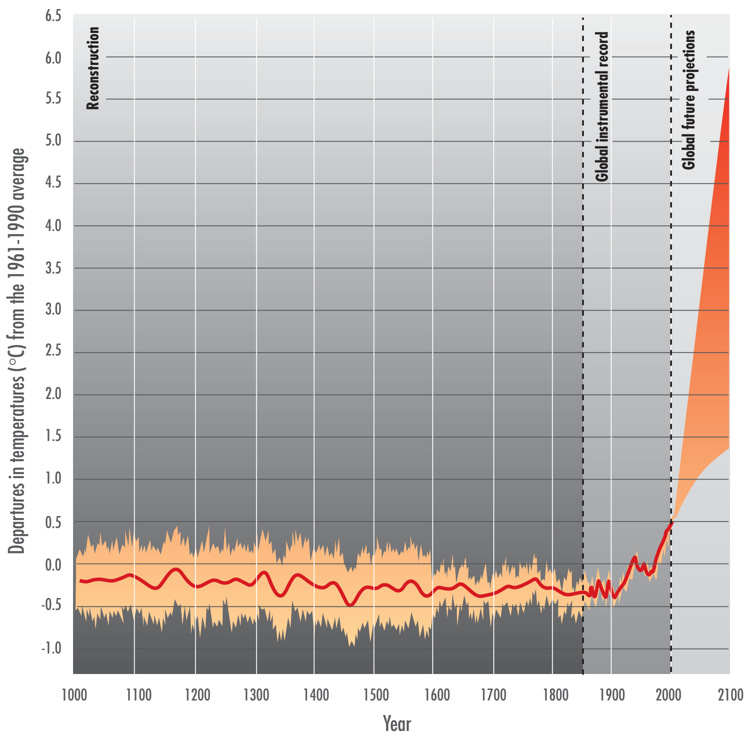


Figure 76. Projected global mean surface temperature changes in the context of recent instrumental records and longer proxy temperature records.

The TAR provides relatively little information on future climate change at the regional level beyond the now fairly confident expectation that continental areas will warm more than the oceans. Future sea-level changes will not be uniformly distributed around the globe. Coupled-model experiments suggest that regional responses to global climate change could differ significantly due to regional differences in heating and circulation changes. There is no evidence that the nature of El Niño and Southern Oscillation events or the frequency, distribution and intensity of tropical cyclones will change with increasing greenhouse gas concentrations. However, it is likely that any changes in tropical cyclone frequency that do occur due to climate change will be small in comparison to their observed natural variability, which is considerable.

Conclusions

The IPCC Third Assessment Report on the Scientific Basis of Climate Change provides a comprehensive and up-to-date overview of what is currently known, and not known, about the science of climate change and what needs to be done to increase understanding in the present areas of uncertainty. While concluding that '…most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations' and indicating that, for the full range of plausible non-intervention emission scenarios considered by the IPCC, 'global average temperatures and sea levels are expected to rise' throughout the twenty-first century and beyond, the Report also draws attention to many gaps in information and many uncertainties remaining in the underlying science (see opposite page).

There are still many uncertainties

The aim of this publication is to present the scientific basis for greenhouse-gas-induced climate change within the context of a complex, highly-interactive, naturally-variable and human-influenced global climate system. It is clear, as documented in the IPCC Third Assessment Report, that we have significantly advanced our understanding of the science of the climate system, our knowledge of the factors that induce climate to change over a wide range of time-scales and our ability to construct computer models that can simulate the behaviour of the climate system under a range of possible forcing scenarios. However, in a scientific sense, many uncertainties still exist and there is a significant challenge ahead to extend our detailed knowledge of the workings of the climate system and to improve the accuracy and relevance of future projections.

Many factors continue to limit the ability to understand, detect and predict climate change. The IPCC Third Assessment Report (TAR) has highlighted nine broad areas where scientists should direct their attention most urgently:

- Arrest the decline of observational networks in many parts of the world.
- Expand the available observational data to provide long-term records with increased temporal and spatial coverage.
- Better estimate future emissions and concentrations of greenhouse gases and aerosols.
- Understand more completely the dominant processes and feedbacks of the climate system.
- Address more completely the patterns of long-term climate variability.
- Explore more fully the probabilistic character of future climate states by developing multiple ensembles of model calculations.
- Improve the integrated hierarchy of global and regional climate models with emphasis on improving the simulation of regional impacts and extreme weather events.
- Link physical climate-biogeochemical models with models of the human system.
- Accelerate progress in understanding climate change by strengthening the international framework needed to coordinate national and institutional efforts.

The basic infrastructure to advance our understanding on these issues is already in place, through such international programs and mechanisms as the World Climate Programme, the World Climate Research Programme, the Climate Agenda and the Global Climate Observing System, and through the infrastucture of international programs and agencies such as the World Meteorological Organization, the United Nations Environment Programme and the Intergovernmental Oceanographic Commission.

Our future climate

The climate of the earth is, as we have seen, determined by a complex interplay of driving forces. While we can understand broadly what these forces are and, in many cases, can measure them and capture their essence in physical and mathematical detail, putting it all together to describe the exact state of the global climate, remains a huge challenge. It would be difficult enough if climate were static but, as history has shown us, even without the efforts of humanity, change is an innate characteristic of climate – from the subtle and not-so-subtle seasonal and interannual variations that we have all experienced through to the large scale and sometimes cataclysmic changes on geological timescales that we have been able to infer from proxy records.

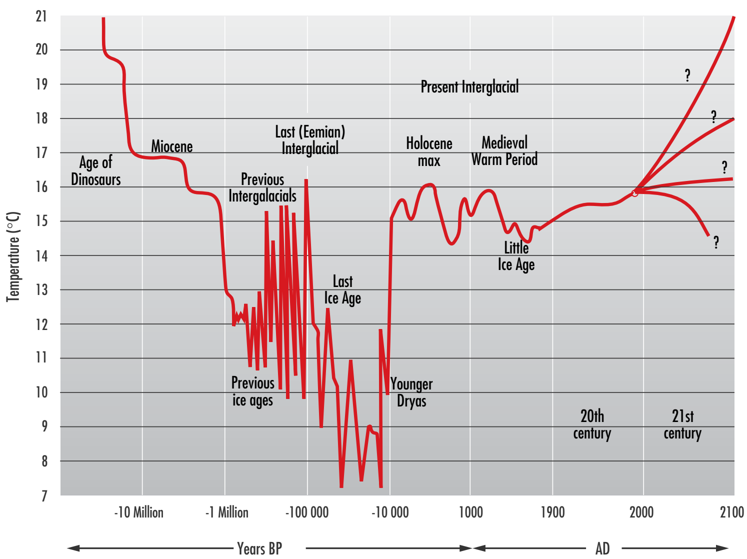


Figure 77. A schematic representation of recent climate trends and future projections in historical perspective. The 20th and 21st centuries are shown to the same (linear) scale. Earlier periods are shown in terms of increasing powers of ten years ago but are linear within each period. The challenge remains to understand how the complex interplay of natural and anthropogenic driving forces will impact on the earth's climate into and beyond the 21st century.

The scientific debate of the last two or three decades on global warming has brought climate forcefully to the attention of governments, opening it up to a level of international political debate rarely encountered by a scientific issue. But as scientists, policymakers and the community at large increasingly focus on the human-induced elements of climate change, it is important to retain a perspective of the bigger climatic picture. Climate has always changed and it will continue to do so (Figure 77). But that does not mean we should underestimate concerns about the changes that human activities, such as fossil fuel combustion and changing land use patterns, may lead to. Humans and human civilizations have developed at a time in the earth's history when climate, in a geological sense, has been relatively stable, and that stability has been a major factor in the evolution and development of our society.

The best resource we have in trying to determine where climate will go in the future is understanding – understanding what drives climate and how the different driving forces, on all scales and from all sources, interact and influence each other. The climate science community around the world shares a commitment to this challenge, from global climate monitoring systems to internationally coordinated research programs to provision of scientific advice to policymakers. Through the work of bodies such as the Intergovernmental Panel on Climate Change (IPCC), underpinned by the efforts of the World Climate Programme and the Global Climate Observing System, these elements come together to ensure that our understanding of climate and climate change is systematically advanced, that uncertainties are reduced, that a balanced perspective is maintained and that key messages are delivered clearly and objectively.

This booklet has attempted to summarise the state of knowledge and understanding as the IPCC begins its Fourth Assessment Report.

Glossary of terms

Aerosols
A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 µm and residing in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in two ways: directly through scattering and absorbing radiation, and indirectly through acting as condensation nuclei for cloud formation or modifying the optical properties and lifetime of clouds. The term has also come to be associated, erroneously, with the propellant used in 'aerosol sprays'.
See: Indirect aerosol effect.

Albedo
The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow covered surfaces have a high albedo; the albedo of soils ranges from high to low; vegetation covered surfaces and oceans have a low albedo. The earth's albedo varies mainly through varying cloudiness, snow, ice, leaf area and land cover changes.

Anthropogenic
Resulting from or produced by human beings.

Biomass
The total mass of living organisms in a given area or volume; recently dead plant material is often included as dead biomass.

Biosphere (terrestrial and marine)
The part of the earth system comprising all ecosystems and living organisms, in the atmosphere, on land (terrestrial biosphere) or in the oceans (marine biosphere), including derived dead organic matter, such as litter, soil organic matter and oceanic detritus.

Black carbon
Operationally defined species based on measurement of light absorption and chemical reactivity and/or thermal stability; consists of soot, charcoal, and/or possible light-absorbing refractory organic matter.

Carbon cycle
The term used to describe the flow of carbon (in various forms, e.g. as carbon dioxide) through the atmosphere, ocean, terrestrial biosphere and lithosphere.

Climate change
Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines 'climate change' as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between 'climate change' attributable to human activities altering the atmospheric composition, and 'climate variability' attributable to natural causes.
See: Climate variability.

Climate feedback
An interaction mechanism between processes in the climate system is called a climate feedback, when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it.

Climate prediction
A climate prediction or climate forecast is the result of an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future, e.g. at seasonal, interannual or long-term time-scales.
See: Climate projection and Climate (change) scenario.

Climate projection

A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasise that climate projections depend upon the emission/concentration/ radiative forcing scenario used, which are based on assumptions, concerning, e.g., future socio-economic and technological developments, that may or may not be realised, and are therefore subject to substantial uncertainty.

Climate scenario

A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.

Climate sensitivity

In IPCC reports, equilibrium climate sensitivity refers to the equilibrium change in global mean surface temperature following a doubling of the atmospheric (equivalent) CO_2 concentration. More generally, equilibrium climate sensitivity refers to the equilibrium change in surface air temperature following a unit change in radiative forcing (°C/W m^{-2}).

Climate system

The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings, such as volcanic eruptions, solar variations and human-induced forcings such as the changing composition of the atmosphere and land-use change.

Climate variability

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See: Climate change.

Climatic Optimum

Also referred to as the Holocene Maximum, the time period between 4,000 and 7,000 years ago when global temperatures reached as high as 2.0°C warmer than present.

Cryosphere

The component of the climate system consisting of all snow, ice and permafrost on and beneath the surface of the earth and ocean.

Diurnal temperature range

The difference between the maximum and minimum temperature during a day.

Drought

The phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems.

Eemian

The last inter-glacial period from 130,000 to 75,000 years ago.

El Niño-Southern Oscillation (ENSO)

El Niño, in its original sense, is a warm water current which periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. This oceanic event is associated with a fluctuation of the intertropical surface pressure pattern and circulation in the Indian and Pacific oceans, called the Southern Oscillation. This coupled atmosphere-ocean phenomenon is collectively known as El Niño-Southern Oscillation, or ENSO. During an El Niño event, the prevailing trade winds weaken and the equatorial countercurrent strengthens, causing warm surface waters in the Indonesian area to flow eastward to overlie the cold waters of the Peru current. This event has great impact on the wind, sea-surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world. The opposite of an El Niño event is called La Niña.

Emission scenario
A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g. greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change) and their key relationships. Concentration scenarios, derived from emission scenarios, are used as input into a climate model to compute climate projections.

Energy balance
Averaged over the globe and over longer time periods, the energy budget of the climate system must be in balance. Because the climate system derives all its energy from the sun, this balance implies that, globally, the amount of incoming solar radiation must on average be equal to the sum of the outgoing reflected solar radiation and the outgoing infrared radiation emitted by the climate system. A perturbation of this global radiation balance, be it human induced or natural, is called radiative forcing.

Evapotranspiration
The combined process of evaporation from the earth's surface and transpiration from vegetation.

External forcing
See: Climate system.

Extreme weather event
An extreme weather event is an event that is rare within its statistical reference distribution at a particular place. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile. By definition, the characteristics of what is called extreme weather may vary from place to place. An extreme climate event is an average of a number of weather events over a certain period of time, an average which is itself extreme (e.g. rainfall over a season).

General Circulation
The large-scale motions of the atmosphere and the ocean as a consequence of differential heating on a rotating earth, aiming to restore the energy balance of the system through transport of heat and momentum.

Global surface temperature
The global surface temperature is the area-weighted global average of (i) the sea-surface temperature over the oceans (i.e. the subsurface bulk temperature in the first few meters of the ocean), and (ii) the surface-air temperature over land at 1.5 m above the ground.

Global Warming Potential (GWP)
An index, describing the radiative characteristics of well mixed greenhouse gases, that represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide.

Greenhouse effect
Greenhouse gases effectively absorb infrared radiation emitted by the earth's surface, by the atmosphere itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the earth's surface. Thus greenhouse gases trap heat within the surface-troposphere system. This is called the natural green-

house effect. Atmospheric radiation is strongly coupled to the temperature of the level at which it is emitted. In the troposphere the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, -18°C, in balance with the net incoming solar radiation, whereas the earth's surface is kept at a much higher temperature of, on average, +15°C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing, an imbalance that can only be compensated for by an increase of the temperature of the surface-troposphere system. This is the enhanced greenhouse effect.

Greenhouse gas
Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the earth's atmosphere. Moreover there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Heat island
An area within an urban area characterized by ambient temperatures higher than those of the surrounding area because of the absorption of solar energy by materials like asphalt.

Hydrosphere
The component of the climate system comprising liquid surface and subterranean water, such as oceans, seas, rivers, fresh water lakes, underground water etc.

Infrared radiation
Radiation emitted by the earth's surface, the atmosphere and the clouds. It is also known as terrestrial or long wave radiation. Infrared radiation has a distinctive range of wavelengths ('spectrum') longer than the wavelength of the red colour in the visible part of the spectrum. The spectrum of infrared radiation is practically distinct from that of solar or short wave radiation because of the difference in temperature between the sun and the earth-atmosphere system.

Land-use change
A change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land-use change may have an impact on the albedo, evapotranspiration, sources and sinks of greenhouse gases, or other properties of the climate system and may thus have an impact on climate, locally or globally.

La Niña
See: El Niño-Southern Oscillation.

Lithosphere
The upper layer of the solid earth, both continental and oceanic, which comprises all crustal rocks and the cold, mainly elastic, part of the uppermost mantle. Volcanic activity, although part of the lithosphere, is not considered as part of the climate system, but acts as an external forcing factor.

Little Ice Age
Refers to a cooling of temperatures (1-2 degrees lower than they are now) that occurred in the northern hemisphere and is thought to have spanned the years 1450 to 1850.

Mean sea level
See: Relative sea level.

Milankovitch cycles
Milankovich cycles are cycles in the earth's orbit that influence the amount of solar radiation striking different parts of the earth at different times of year. They are named after a Serbian mathematician, Milutin Milankovitch, who explained how these orbital cycles cause the advance and retreat of the polar ice caps.

Mitigation
A human intervention to reduce the sources or enhance the sinks of greenhouse gases.

Non-linearity
A process is called ‘non-linear’ when there is no simple proportional relation between cause and effect. The climate system contains many such non-linear processes, resulting in a system with a potentially very complex behaviour. Such complexity may lead to rapid climate change.

North Atlantic Oscillation (NAO)
The North Atlantic Oscillation 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.

Ocean conveyor belt
The theoretical route by which water circulates around the entire global ocean, driven by wind and the thermohaline circulation.

Ozone layer
The stratosphere contains a layer in which the concentration of ozone is greatest, the so called ozone layer. The layer extends from about 12 to 40 km. The ozone concentration reaches a maximum between about 20 and 25 km. This layer is being depleted by human emissions of chlorine and bromine compounds. Every year, during the southern hemisphere spring, a very strong depletion of the ozone layer takes place over the Antarctic region, also caused by human-made chlorine and bromine compounds in combination with the specific meteorological conditions of that region. This phenomenon is called the ozone hole.

Parametrisation
In climate models, this term refers to the technique of representing processes, that cannot be explicitly resolved at the spatial or temporal resolution of the model (sub-grid scale processes), by relationships between the area or time averaged effect of such sub-grid scale processes and the larger scale flow.

Proxy
A proxy climate indicator is a local record that is interpreted, using physical and biophysical principles, to represent some combination of climate-related variations back in time. Climate related data derived in this way are referred to as proxy data. Examples of proxies are: tree ring records, characteristics of corals, and various data derived from ice cores.

Radiative balance
See: Energy balance.

Radiative forcing
Radiative forcing is the change in the net vertical irradiance (expressed in Watts per square metre: Wm^{-2}) at the tropopause due to an internal change or a change in the external forcing of the climate system, such as, for example, a change in the concentration of carbon dioxide or the output of the sun. Usually radiative forcing is computed after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with all tropospheric properties held fixed at their unperturbed values. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for.

Relative sea level
Sea level measured by a tide gauge with respect to

the land upon which it is situated. Mean Sea Level (MSL) is normally defined as the average Relative Sea Level over a period, such as a month or a year, long enough to average out transients such as waves.

Sink
Any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere.

Soil moisture
Water stored in or at the land surface and available for evaporation.

Solar activity
The sun exhibits periods of high activity observed in numbers of sunspots, as well as radiative output, magnetic activity, and emission of high energy particles. These variations take place on a range of time-scales from millions of years to minutes.
See: Solar cycle.

Solar ('11 year') cycle
A quasi-regular modulation of solar activity with varying amplitude and a period of between 9 and 13 years.

Solar radiation
Radiation emitted by the sun. It is also referred to as short wave radiation. Solar radiation has a distinctive range of wavelengths (spectrum) determined by the temperature of the sun.
See: Infrared radiation.

Stabilisation
The achievement of stabilisation of atmospheric concentrations of one or more greenhouse gases (e.g., carbon dioxide or a CO_2-equivalent basket of greenhouse gases).

Stratosphere
The highly stratified region of the atmosphere above the troposphere extending from about 10 km (ranging from 9 km in high latitudes to 16 km in the tropics on average) to about 50 km.

Sunspots
Small dark areas on the sun. The number of sunspots is higher during periods of high solar activity, and varies in particular with the solar cycle.

Thermal expansion
In connection with sea level, this refers to the increase in volume (and decrease in density) that results from warming water. A warming of the ocean leads to an expansion of the ocean volume and hence an increase in sea level.

Thermohaline circulation
Large-scale density-driven circulation in the ocean, caused by differences in temperature and salinity. In the North Atlantic the thermohaline circulation consists of warm surface water flowing northward and cold deep water flowing southward, resulting in a net poleward transport of heat. The surface water sinks in highly restricted sinking regions located in high latitudes.

Tropopause
The boundary between the troposphere and the stratosphere.

Troposphere
The lowest part of the atmosphere from the surface to about 10 km in altitude in mid-latitudes (ranging from 9 km in high latitudes to 16 km in the tropics on average) where clouds and 'weather' phenomena occur. In the troposphere temperatures generally decrease with height.

Uncertainty
An expression of the degree to which a value (e.g. the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g. a range of values calculated by various mod-

els) or by qualitative statements (e.g., reflecting the judgement of a team of experts).

Upwelling
Transport of deeper water to the surface, usually caused by horizontal movements of surface water.

Younger Dryas
Approximately 1300 years of severely cold climate experienced by North America, Europe and Western Asia following the last ice age, about 12,700 years ago.

Acronyms and abbreviations

AGBM	Ad hoc Group on the Berlin Mandate
AGCM	Atmospheric General Circulation Model
AGGG	Advisory Group on Greenhouse Gases
BMRC	Bureau of Meteorology Research Centre
BP	Before Present
CF_4	perfluoromethane
CFC	Chlorofluorocarbons
CFC-11	trichlorofluoromethane
CH_4	methane
CO_2	carbon dioxide
COP/FCCC	Conference of the Parties to the Framework Convention on Climate Change
CSD	Commission for Sustainable Development
EB-UDM	Energy Balance – Upwelling Diffusion Model
ENSO	El Niño - Southern Oscillation
EPAC	Eastern Pacific region
FAR	First Assessment Report (of IPCC)
FCCC	UN Framework Convention on Climate Change
FWCC	First World Climate Conference
GAW	Global Atmosphere Watch
GCM	General Circulation Model
GCOS	Global Climate Observing System
GDD	Growing Degree Day
GHG	Greenhouse Gas
GOOS	Global Ocean Observing System
GSN	GCOS Surface Network
GTOS	Global Terrestrial Observing System
GtC	Gigatonnes of Carbon
GUAN	GCOS Upper Air Network
HCFC	hydrochlorofluorocarbons
HFC	hydrofluorocarbons
ICAO	International Civil Aviation Organization
ICSU	International Council for Science
IEA	International Energy Agency
IGBP	International Geosphere-Biosphere Programme
IGOSS	Integrated Global Ocean Services System
INC(D)	Intergovernmental Negotiating Committee on Desertification
INC/FCCC	Intergovernmental Negotiating Committee for a Framework Convention on Climate Change
INDO	Indonesian region
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
K	Kelvin (0°C = 273K approximately)
LAM	Local Area Model
LW	long wave
MSLP	Mean sea-level pressure
N_2O	nitrous oxide
NAO	North Atlantic Oscillation
OECD	Organisation for Economic Cooperation and Development
OGCM	Ocean General Circulation Model
OH	tropospheric hydroxyl
PDF	Probability Distribution Function
PDO	Pacific Decadal Oscillation
ppmv	parts per million (10^6) by volume
ppbv	parts per billion (10^9) by volume
pptv	parts per trillion (10^{12}) by volume
PW	Petawatts (1 PW = 10^{15} W)
SAR	Second Assessment Report (of the IPCC)
SBSTA	Subsidiary Body for Scientific and Technological Advice (of UN FCCC)
SOI	Southern Oscillation Index
SPEC	The IPCC Special Report on Radiative Forcing and Climate Change, 1994
SPM	Summary for Policymakers of the IPCC Third Assessment Report
SRES	Special Report on Emissions Scenarios (of IPCC)
SRLUCF	Special Report on Land Use, Land Use Change and Forestry (of IPCC)
SRTT	Special Report on Methodological and Technological Issues in Technological Transfer (of IPCC)
SST	Sea-surface temperature
SUPP	The Supplementary Report to the IPCC Scientific Assessment, 1992

SW	short wave
SWCC	Second World Climate Conference
TAR	Third Assessment Report (of the IPCC)
TFI	Task Force on Inventories
TOA	Top of the Atmosphere
UHI	Urban Heat Island
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNGA	United Nations General Assembly
W	Watt
WCP	World Climate Programme
WCRP	World Climate Research Programme
WG	Working Group of the IPCC
WGI	Working Group One of the IPCC (Science)
WGII	Working Group Two of the IPCC (Impacts, Adaptation and Vulnerability)
WGIII	Working Group Three of the IPCC (Mitigation)
WMO	World Meteorological Organization
WSSD	World Summit on Sustainable Development

Further reading

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IPCC 2001. *Climate Change 2001: Synthesis Report - A contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Watson, R.T. and the Core Writing Team (Eds)], Cambridge University Press, UK, 398 pp.

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IPCC 2000. *Emissions Scenarios. 2000 - Special Report of the Intergovernmental Panel on Climate Change* [Nebojsa Nakicenovic and Rob Swart (Eds.)], Cambridge University Press, UK, 570 pp.

The above IPCC reports and other material about the IPCC can be accessed at the IPCC website (www.ipcc.ch). The Bureau of Meteorology website (www.bom.gov.au) contains a wide range of information on Australian climate and links to other useful sites.