

**From the report accepted by Working Group I  
of the Intergovernmental Panel on Climate Change  
but not approved in detail**

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## **Frequently Asked Questions**

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### **FAQ Citation:**

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### **When referencing the group of FAQs, please cite as:**

IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

## Frequently Asked Question 1.1

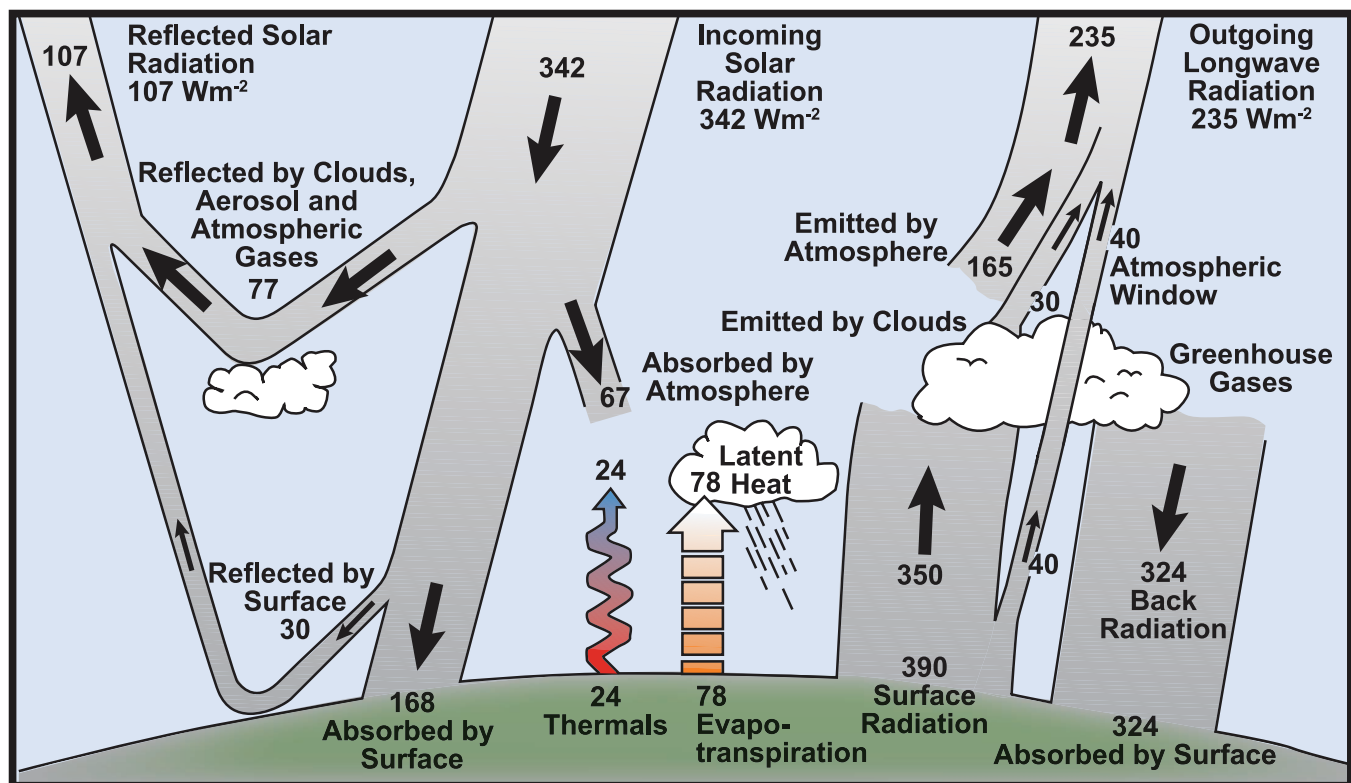
**What Factors Determine Earth's Climate?**

The climate system is a complex, interactive system consisting of the atmosphere, land surface, snow and ice, oceans and other bodies of water, and living things. The atmospheric component of the climate system most obviously characterises climate; climate is often defined as 'average weather'. Climate is usually described in terms of the mean and variability of temperature, precipitation and wind over a period of time, ranging from months to millions of years (the classical period is 30 years). The climate system evolves in time under the influence of its own internal dynamics and due to changes in external factors that affect climate (called 'forcings'). External forcings include natural phenomena such as volcanic eruptions and solar variations, as well as human-induced changes in atmospheric composition. Solar radiation powers the climate system. There are three fundamental ways to change the radiation balance of the Earth: 1) by changing the incoming solar radiation (e.g., by changes in Earth's orbit or in the Sun itself); 2) by changing the fraction of solar radiation that is reflected (called

'albedo'; e.g., by changes in cloud cover, atmospheric particles or vegetation); and 3) by altering the longwave radiation from Earth back towards space (e.g., by changing greenhouse gas concentrations). Climate, in turn, responds directly to such changes, as well as indirectly, through a variety of feedback mechanisms.

The amount of energy reaching the top of Earth's atmosphere each second on a surface area of one square metre facing the Sun during daytime is about 1,370 Watts, and the amount of energy per square metre per second averaged over the entire planet is one-quarter of this (see Figure 1). About 30% of the sunlight that reaches the top of the atmosphere is reflected back to space. Roughly two-thirds of this reflectivity is due to clouds and small particles in the atmosphere known as 'aerosols'. Light-coloured areas of Earth's surface – mainly snow, ice and deserts – reflect the remaining one-third of the sunlight. The most dramatic change in aerosol-produced reflectivity comes when major volcanic eruptions eject material very high into the atmosphere. Rain typically

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**FAQ 1.1, Figure 1.** Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. Source: Kiehl and Trenberth (1997).

clears aerosols out of the atmosphere in a week or two, but when material from a violent volcanic eruption is projected far above the highest cloud, these aerosols typically influence the climate for about a year or two before falling into the troposphere and being carried to the surface by precipitation. Major volcanic eruptions can thus cause a drop in mean global surface temperature of about half a degree celsius that can last for months or even years. Some man-made aerosols also significantly reflect sunlight.

The energy that is not reflected back to space is absorbed by the Earth's surface and atmosphere. This amount is approximately 240 Watts per square metre ( $\text{W m}^{-2}$ ). To balance the incoming energy, the Earth itself must radiate, on average, the same amount of energy back to space. The Earth does this by emitting outgoing longwave radiation. Everything on Earth emits longwave radiation continuously. That is the heat energy one feels radiating out from a fire; the warmer an object, the more heat energy it radiates. To emit  $240 \text{ W m}^{-2}$ , a surface would have to have a temperature of around  $-19^\circ\text{C}$ . This is much colder than the conditions that actually exist at the Earth's surface (the global mean surface temperature is about  $14^\circ\text{C}$ ). Instead, the necessary  $-19^\circ\text{C}$  is found at an altitude about 5 km above the surface.

The reason the Earth's surface is this warm is the presence of greenhouse gases, which act as a partial blanket for the longwave radiation coming from the surface. This blanketing is known as the natural greenhouse effect. The most important greenhouse gases are water vapour and carbon dioxide. The two most abundant constituents of the atmosphere – nitrogen and oxygen – have no such effect. Clouds, on the other hand, do exert a blanketing effect similar to that of the greenhouse gases; however, this effect is offset by their reflectivity, such that on average, clouds tend to have a cooling effect on climate (although locally one can feel the warming effect: cloudy nights tend to remain warmer than clear nights because the clouds radiate longwave energy back down to the surface). Human activities intensify the blanketing effect through the release of greenhouse gases. For instance, the amount of carbon dioxide in the atmosphere has increased by about 35% in the industrial era, and this increase is known to be due to human activities, primarily the combustion of fossil fuels and removal of forests. Thus, humankind has dramatically altered the chemical composition of the global atmosphere with substantial implications for climate.

Because the Earth is a sphere, more solar energy arrives for a given surface area in the tropics than at higher latitudes, where

sunlight strikes the atmosphere at a lower angle. Energy is transported from the equatorial areas to higher latitudes via atmospheric and oceanic circulations, including storm systems. Energy is also required to evaporate water from the sea or land surface, and this energy, called latent heat, is released when water vapour condenses in clouds (see Figure 1). Atmospheric circulation is primarily driven by the release of this latent heat. Atmospheric circulation in turn drives much of the ocean circulation through the action of winds on the surface waters of the ocean, and through changes in the ocean's surface temperature and salinity through precipitation and evaporation.

Due to the rotation of the Earth, the atmospheric circulation patterns tend to be more east-west than north-south. Embedded in the mid-latitude westerly winds are large-scale weather systems that act to transport heat toward the poles. These weather systems are the familiar migrating low- and high-pressure systems and their associated cold and warm fronts. Because of land-ocean temperature contrasts and obstacles such as mountain ranges and ice sheets, the circulation system's planetary-scale atmospheric waves tend to be geographically anchored by continents and mountains although their amplitude can change with time. Because of the wave patterns, a particularly cold winter over North America may be associated with a particularly warm winter elsewhere in the hemisphere. Changes in various aspects of the climate system, such as the size of ice sheets, the type and distribution of vegetation or the temperature of the atmosphere or ocean will influence the large-scale circulation features of the atmosphere and oceans.

There are many feedback mechanisms in the climate system that can either amplify ('positive feedback') or diminish ('negative feedback') the effects of a change in climate forcing. For example, as rising concentrations of greenhouse gases warm Earth's climate, snow and ice begin to melt. This melting reveals darker land and water surfaces that were beneath the snow and ice, and these darker surfaces absorb more of the Sun's heat, causing more warming, which causes more melting, and so on, in a self-reinforcing cycle. This feedback loop, known as the 'ice-albedo feedback', amplifies the initial warming caused by rising levels of greenhouse gases. Detecting, understanding and accurately quantifying climate feedbacks have been the focus of a great deal of research by scientists unravelling the complexities of Earth's climate.

## Frequently Asked Question 1.2

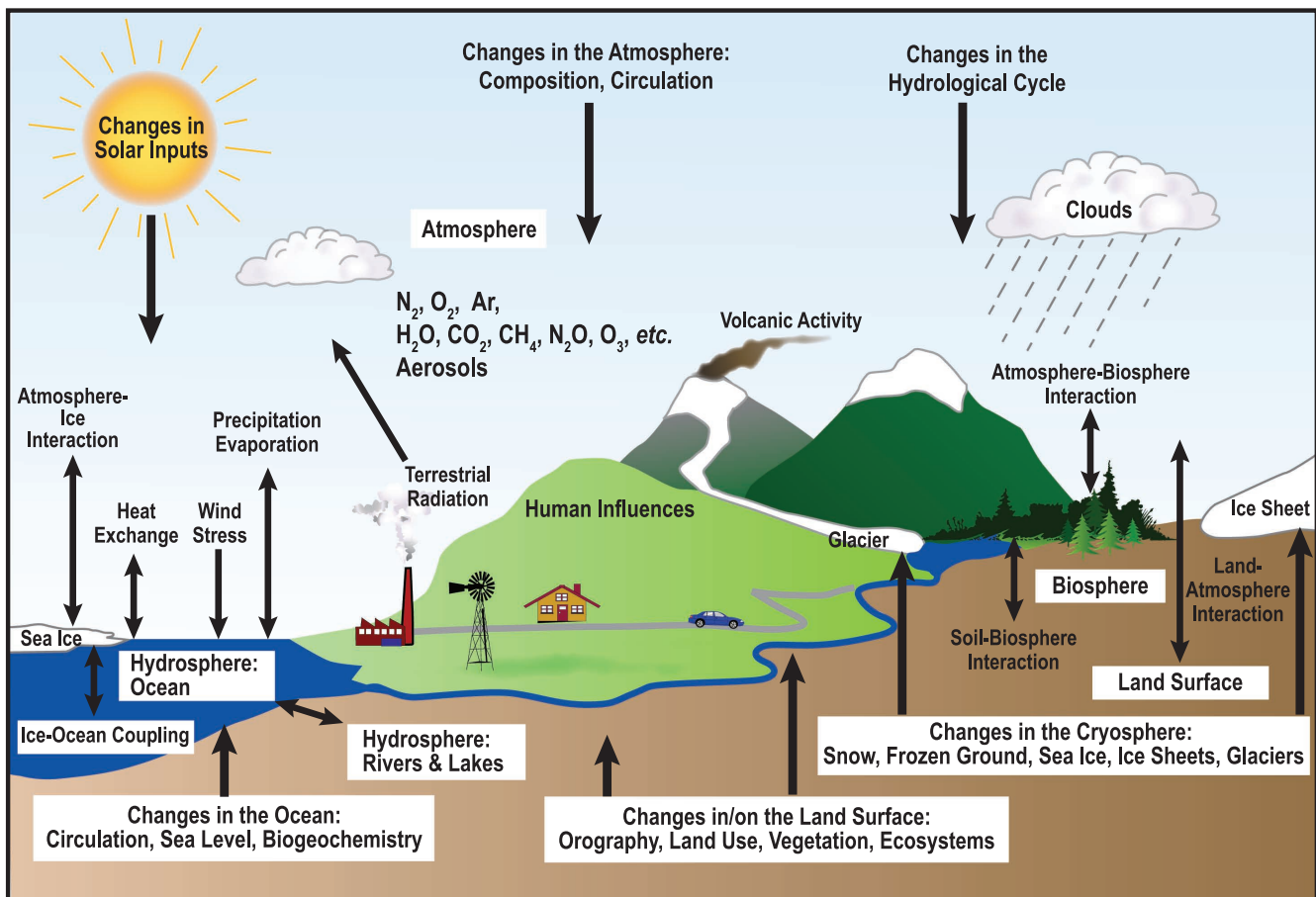
## What is the Relationship between Climate Change and Weather?

Climate is generally defined as average weather, and as such, climate change and weather are intertwined. Observations can show that there have been changes in weather, and it is the statistics of changes in weather over time that identify climate change. While weather and climate are closely related, there are important differences. A common confusion between weather and climate arises when scientists are asked how they can predict climate 50 years from now when they cannot predict the weather a few weeks from now. The chaotic nature of weather makes it unpredictable beyond a few days. Projecting changes in climate (i.e., long-term average weather) due to changes in atmospheric composition or other factors is a very different and much more manageable issue. As an analogy, while it is impossible to predict the age at which any particular man will die, we can say with high confidence that the average age of death for men in industrialised countries is about 75. Another common confusion of these issues is thinking

that a cold winter or a cooling spot on the globe is evidence against global warming. There are always extremes of hot and cold, although their frequency and intensity change as climate changes. But when weather is averaged over space and time, the fact that the globe is warming emerges clearly from the data.

Meteorologists put a great deal of effort into observing, understanding and predicting the day-to-day evolution of weather systems. Using physics-based concepts that govern how the atmosphere moves, warms, cools, rains, snows, and evaporates water, meteorologists are typically able to predict the weather successfully several days into the future. A major limiting factor to the predictability of weather beyond several days is a fundamental dynamical property of the atmosphere. In the 1960s, meteorologist Edward Lorenz discovered that very slight differences in initial conditions can produce very different forecast results.

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FAQ 1.2, Figure 1. Schematic view of the components of the climate system, their processes and interactions.



This is the so-called butterfly effect: a butterfly flapping its wings (or some other small phenomenon) in one place can, in principle, alter the subsequent weather pattern in a distant place. At the core of this effect is chaos theory, which deals with how small changes in certain variables can cause apparent randomness in complex systems.

Nevertheless, chaos theory does not imply a total lack of order. For example, slightly different conditions early in its history might alter the day a storm system would arrive or the exact path it would take, but the average temperature and precipitation (that is, climate) would still be about the same for that region and that period of time. Because a significant problem facing weather forecasting is knowing all the conditions at the start of the forecast period, it can be useful to think of climate as dealing with the background conditions for weather. More precisely, climate can be viewed as concerning the status of the entire Earth system, including the atmosphere, land, oceans, snow, ice and living things (see Figure 1) that serve as the global background conditions that determine weather patterns. An example of this would be an El Niño affecting the weather in coastal Peru. The El Niño sets limits on the probable evolution of weather patterns that random effects can produce. A La Niña would set different limits.

Another example is found in the familiar contrast between summer and winter. The march of the seasons is due to changes in the geographical patterns of energy absorbed and radiated away by the Earth system. Likewise, projections of future climate are

shaped by fundamental changes in heat energy in the Earth system, in particular the increasing intensity of the greenhouse effect that traps heat near Earth's surface, determined by the amount of carbon dioxide and other greenhouse gases in the atmosphere. Projecting changes in climate due to changes in greenhouse gases 50 years from now is a very different and much more easily solved problem than forecasting weather patterns just weeks from now. To put it another way, long-term variations brought about by changes in the composition of the atmosphere are much more predictable than individual weather events. As an example, while we cannot predict the outcome of a single coin toss or roll of the dice, we can predict the statistical behaviour of a large number of such trials.

While many factors continue to influence climate, scientists have determined that human activities have become a dominant force, and are responsible for most of the warming observed over the past 50 years. Human-caused climate change has resulted primarily from changes in the amounts of greenhouse gases in the atmosphere, but also from changes in small particles (aerosols), as well as from changes in land use, for example. As climate changes, the probabilities of certain types of weather events are affected. For example, as Earth's average temperature has increased, some weather phenomena have become more frequent and intense (e.g., heat waves and heavy downpours), while others have become less frequent and intense (e.g., extreme cold events).

## Frequently Asked Question 1.3

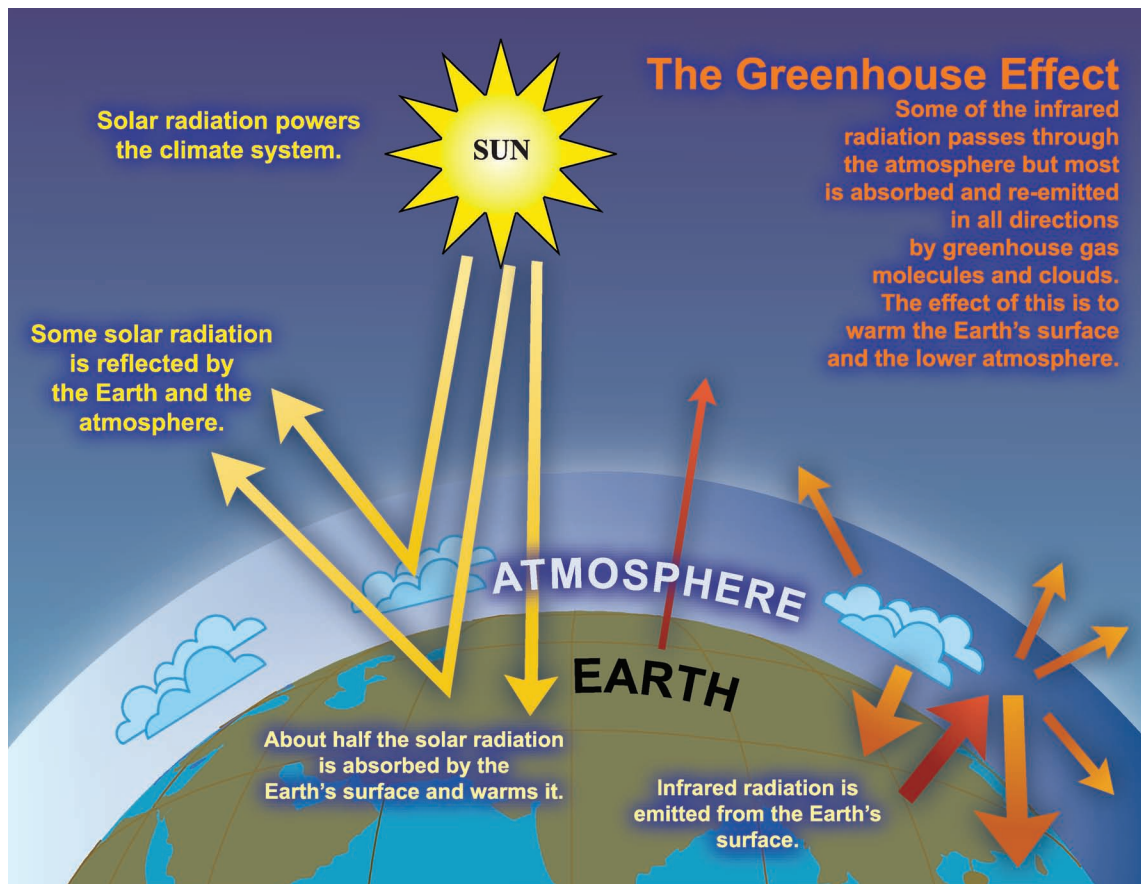
**What is the Greenhouse Effect?**

The Sun powers Earth's climate, radiating energy at very short wavelengths, predominately in the visible or near-visible (e.g., ultraviolet) part of the spectrum. Roughly one-third of the solar energy that reaches the top of Earth's atmosphere is reflected directly back to space. The remaining two-thirds is absorbed by the surface and, to a lesser extent, by the atmosphere. To balance the absorbed incoming energy, the Earth must, on average, radiate the same amount of energy back to space. Because the Earth is much colder than the Sun, it radiates at much longer wavelengths, primarily in the infrared part of the spectrum (see Figure 1). Much of this thermal radiation emitted by the land and ocean is absorbed by the atmosphere, including clouds, and reradiated back to Earth. This is called the greenhouse effect. The glass walls in a greenhouse reduce airflow and increase the temperature of the air inside. Analogously, but through a different physical process, the Earth's greenhouse effect warms the surface of the planet. Without the natural greenhouse effect, the average temperature at Earth's surface would be below the freezing point of water. Thus,

Earth's natural greenhouse effect makes life as we know it possible. However, human activities, primarily the burning of fossil fuels and clearing of forests, have greatly intensified the natural greenhouse effect, causing global warming.

The two most abundant gases in the atmosphere, nitrogen (comprising 78% of the dry atmosphere) and oxygen (comprising 21%), exert almost no greenhouse effect. Instead, the greenhouse effect comes from molecules that are more complex and much less common. Water vapour is the most important greenhouse gas, and carbon dioxide (CO<sub>2</sub>) is the second-most important one. Methane, nitrous oxide, ozone and several other gases present in the atmosphere in small amounts also contribute to the greenhouse effect. In the humid equatorial regions, where there is so much water vapour in the air that the greenhouse effect is very large, adding a small additional amount of CO<sub>2</sub> or water vapour has only a small direct impact on downward infrared radiation. However, in the cold, dry polar regions, the effect of a small increase in CO<sub>2</sub> or

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FAQ 1.3, Figure 1. An idealised model of the natural greenhouse effect. See text for explanation.

water vapour is much greater. The same is true for the cold, dry upper atmosphere where a small increase in water vapour has a greater influence on the greenhouse effect than the same change in water vapour would have near the surface.

Several components of the climate system, notably the oceans and living things, affect atmospheric concentrations of greenhouse gases. A prime example of this is plants taking CO<sub>2</sub> out of the atmosphere and converting it (and water) into carbohydrates via photosynthesis. In the industrial era, human activities have added greenhouse gases to the atmosphere, primarily through the burning of fossil fuels and clearing of forests.

Adding more of a greenhouse gas, such as CO<sub>2</sub>, to the atmosphere intensifies the greenhouse effect, thus warming Earth's climate. The amount of warming depends on various feedback mechanisms. For example, as the atmosphere warms due to rising levels of greenhouse gases, its concentration of water vapour

increases, further intensifying the greenhouse effect. This in turn causes more warming, which causes an additional increase in water vapour, in a self-reinforcing cycle. This water vapour feedback may be strong enough to approximately double the increase in the greenhouse effect due to the added CO<sub>2</sub> alone.

Additional important feedback mechanisms involve clouds. Clouds are effective at absorbing infrared radiation and therefore exert a large greenhouse effect, thus warming the Earth. Clouds are also effective at reflecting away incoming solar radiation, thus cooling the Earth. A change in almost any aspect of clouds, such as their type, location, water content, cloud altitude, particle size and shape, or lifetimes, affects the degree to which clouds warm or cool the Earth. Some changes amplify warming while others diminish it. Much research is in progress to better understand how clouds change in response to climate warming, and how these changes affect climate through various feedback mechanisms.

## Frequently Asked Question 2.1

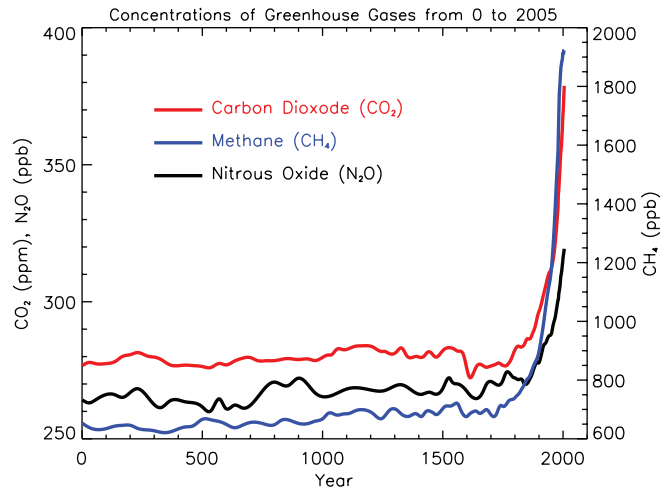
# How do Human Activities Contribute to Climate Change and How do They Compare with Natural Influences?

Human activities contribute to climate change by causing changes in Earth's atmosphere in the amounts of greenhouse gases, aerosols (small particles), and cloudiness. The largest known contribution comes from the burning of fossil fuels, which releases carbon dioxide gas to the atmosphere. Greenhouse gases and aerosols affect climate by altering incoming solar radiation and outgoing infrared (thermal) radiation that are part of Earth's energy balance. Changing the atmospheric abundance or properties of these gases and particles can lead to a warming or cooling of the climate system. Since the start of the industrial era (about 1750), the overall effect of human activities on climate has been a warming influence. The human impact on climate during this era greatly exceeds that due to known changes in natural processes, such as solar changes and volcanic eruptions.

### Greenhouse Gases

Human activities result in emissions of four principal greenhouse gases: carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and the halocarbons (a group of gases containing fluorine, chlorine and bromine). These gases accumulate in the atmosphere, causing concentrations to increase with time. Significant increases in all of these gases have occurred in the industrial era (see Figure 1). All of these increases are attributable to human activities.

- Carbon dioxide has increased from fossil fuel use in transportation, building heating and cooling and the manufacture of cement and other goods. Deforestation releases CO<sub>2</sub> and reduces its uptake by plants. Carbon dioxide is also released in natural processes such as the decay of plant matter.
- Methane has increased as a result of human activities related to agriculture, natural gas distribution and landfills. Methane is also released from natural processes that occur, for example, in wetlands. Methane concentrations are not currently increasing in the atmosphere because growth rates decreased over the last two decades.
- Nitrous oxide is also emitted by human activities such as fertilizer use and fossil fuel burning. Natural processes in soils and the oceans also release N<sub>2</sub>O.
- Halocarbon gas concentrations have increased primarily due to human activities. Natural processes are also a small source. Principal halocarbons include the chlorofluorocarbons (e.g., CFC-11 and CFC-12), which were used extensively as refrigeration agents and in other industrial processes before their presence in the atmosphere was found to cause stratospheric ozone depletion. The abundance of chlorofluorocarbon gases is decreasing as a result of international regulations designed to protect the ozone layer.



**FAQ 2.1, Figure 1.** Atmospheric concentrations of important long-lived greenhouse gases over the last 2,000 years. Increases since about 1750 are attributed to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion air molecules, respectively, in an atmospheric sample. (Data combined and simplified from Chapters 6 and 2 of this report.)

- Ozone is a greenhouse gas that is continually produced and destroyed in the atmosphere by chemical reactions. In the troposphere, human activities have increased ozone through the release of gases such as carbon monoxide, hydrocarbons and nitrogen oxide, which chemically react to produce ozone. As mentioned above, halocarbons released by human activities destroy ozone in the stratosphere and have caused the ozone hole over Antarctica.
- Water vapour is the most abundant and important greenhouse gas in the atmosphere. However, human activities have only a small direct influence on the amount of atmospheric water vapour. Indirectly, humans have the potential to affect water vapour substantially by changing climate. For example, a warmer atmosphere contains more water vapour. Human activities also influence water vapour through CH<sub>4</sub> emissions, because CH<sub>4</sub> undergoes chemical destruction in the stratosphere, producing a small amount of water vapour.
- Aerosols are small particles present in the atmosphere with widely varying size, concentration and chemical composition. Some aerosols are emitted directly into the atmosphere while others are formed from emitted compounds. Aerosols contain both naturally occurring compounds and those emitted as a result of human activities. Fossil fuel and biomass burning have increased aerosols containing sulphur compounds, organic compounds and black carbon (soot). Human activities such as

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surface mining and industrial processes have increased dust in the atmosphere. Natural aerosols include mineral dust released from the surface, sea salt aerosols, biogenic emissions from the land and oceans and sulphate and dust aerosols produced by volcanic eruptions.

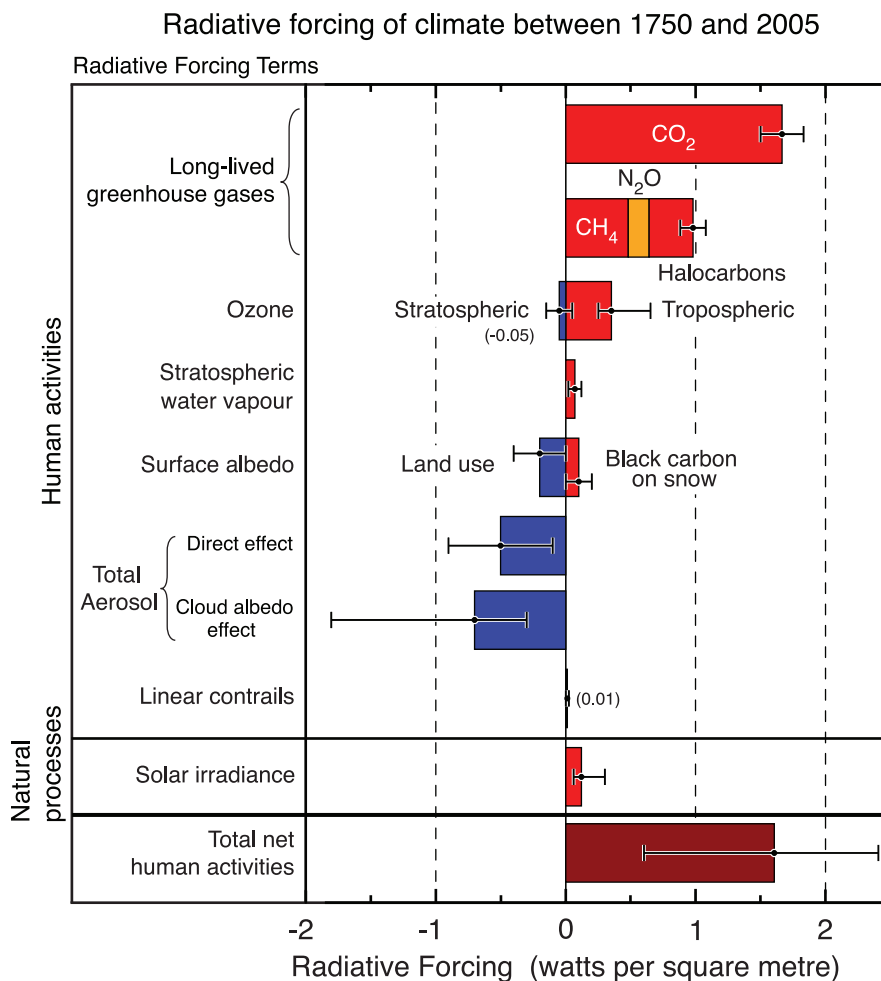
### Radiative Forcing of Factors Affected by Human Activities

The contributions to radiative forcing from some of the factors influenced by human activities are shown in Figure 2. The values reflect the total forcing relative to the start of the industrial era (about 1750). The forcings for all greenhouse gas increases, which are the best understood of those due to human activities, are positive because each gas absorbs outgoing infrared radiation in the atmosphere. Among the greenhouse gases, CO<sub>2</sub> increases have caused the largest forcing over this period. Tropospheric ozone increases have also contributed to warming, while stratospheric ozone decreases have contributed to cooling.

Aerosol particles influence radiative forcing directly through reflection and absorption of solar and infrared radiation in the atmosphere. Some aerosols cause a positive forcing while others cause a negative forcing. The direct radiative forcing summed over all aerosol types is negative. Aerosols also cause a negative radiative forcing indirectly through the changes they cause in cloud properties.

Human activities since the industrial era have altered the nature of land cover over the globe, principally through changes in

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**FAQ 2.1, Figure 2.** Summary of the principal components of the radiative forcing of climate change. All these radiative forcings result from one or more factors that affect climate and are associated with human activities or natural processes as discussed in the text. The values represent the forcings in 2005 relative to the start of the industrial era (about 1750). Human activities cause significant changes in long-lived gases, ozone, water vapour, surface albedo, aerosols and contrails. The only increase in natural forcing of any significance between 1750 and 2005 occurred in solar irradiance. Positive forcings lead to warming of climate and negative forcings lead to a cooling. The thin black line attached to each coloured bar represents the range of uncertainty for the respective value. (Figure adapted from Figure 2.20 of this report.)

### FAQ 2.1, Box 1: What is Radiative Forcing?

What is radiative forcing? The influence of a factor that can cause climate change, such as a greenhouse gas, is often evaluated in terms of its radiative forcing. Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered. The word radiative arises because these factors change the balance between incoming solar radiation and outgoing infrared radiation within the Earth's atmosphere. This radiative balance controls the Earth's surface temperature. The term forcing is used to indicate that Earth's radiative balance is being pushed away from its normal state.

Radiative forcing is usually quantified as the 'rate of energy change per unit area of the globe as measured at the top of the atmosphere', and is expressed in units of 'Watts per square metre' (see Figure 2). When radiative forcing from a factor or group of factors is evaluated as positive, the energy of the Earth-atmosphere system will ultimately increase, leading to a warming of the system. In contrast, for a negative radiative forcing, the energy will ultimately decrease, leading to a cooling of the system. Important challenges for climate scientists are to identify all the factors that affect climate and the mechanisms by which they exert a forcing, to quantify the radiative forcing of each factor and to evaluate the total radiative forcing from the group of factors.

croplands, pastures and forests. They have also modified the reflective properties of ice and snow. Overall, it is likely that more solar radiation is now being reflected from Earth's surface as a result of human activities. This change results in a negative forcing.

Aircraft produce persistent linear trails of condensation ('contrails') in regions that have suitably low temperatures and high humidity. Contrails are a form of cirrus cloud that reflect solar radiation and absorb infrared radiation. Linear contrails from global aircraft operations have increased Earth's cloudiness and are estimated to cause a small positive radiative forcing.

### **Radiative Forcing from Natural Changes**

Natural forcings arise due to solar changes and explosive volcanic eruptions. Solar output has increased gradually in the industrial era, causing a small positive radiative forcing (see Figure 2). This is in addition to the cyclic changes in solar radiation that

follow an 11-year cycle. Solar energy directly heats the climate system and can also affect the atmospheric abundance of some greenhouse gases, such as stratospheric ozone. Explosive volcanic eruptions can create a short-lived (2 to 3 years) negative forcing through the temporary increases that occur in sulphate aerosol in the stratosphere. The stratosphere is currently free of volcanic aerosol, since the last major eruption was in 1991 (Mt. Pinatubo).

The differences in radiative forcing estimates between the present day and the start of the industrial era for solar irradiance changes and volcanoes are both very small compared to the differences in radiative forcing estimated to have resulted from human activities. As a result, in today's atmosphere, the radiative forcing from human activities is much more important for current and future climate change than the estimated radiative forcing from changes in natural processes.



### Frequently Asked Question 3.1

## How are Temperatures on Earth Changing?

*Instrumental observations over the past 157 years show that temperatures at the surface have risen globally, with important regional variations. For the global average, warming in the last century has occurred in two phases, from the 1910s to the 1940s (0.35°C), and more strongly from the 1970s to the present (0.55°C). An increasing rate of warming has taken place over the last 25 years, and 11 of the 12 warmest years on record have occurred in the past 12 years. Above the surface, global observations since the late 1950s show that the troposphere (up to about 10 km) has warmed at a slightly greater rate than the surface, while the stratosphere (about 10–30 km) has cooled markedly since 1979. This is in accord with physical expectations and most model results. Confirmation of global warming comes from warming of the oceans, rising sea levels, glaciers melting, sea ice retreating in the Arctic and diminished snow cover in the Northern Hemisphere.*

There is no single thermometer measuring the global temperature. Instead, individual thermometer measurements taken every day at several thousand stations over the land areas of the world are combined with thousands more measurements of sea surface temperature taken from ships moving over the oceans to produce an estimate of global average temperature every month. To obtain consistent changes over time, the main analysis is actually of anomalies (departures from the climatological mean at each site) as these are more robust to changes in data availability. It is now possible to use these measurements from 1850 to the present, although coverage is much less than global in the second half of the 19th century, is much better after 1957 when measurements began in Antarctica, and best after about 1980, when satellite measurements began.

Expressed as a global average, surface temperatures have increased by about 0.74°C over the past hundred years (between 1906 and 2005; see Figure 1). However, the warming has been neither steady nor the same in different seasons or in different locations. There was not much overall change from 1850 to about 1915, aside from ups and downs associated with natural variability but which may have also partly arisen from poor sampling. An increase (0.35°C) occurred in the global average temperature from the 1910s to the 1940s, followed by a slight cooling (0.1°C), and then a rapid warming (0.55°C) up to the end of 2006 (Figure 1). The warmest years of the series are 1998 and 2005 (which are statistically indistinguishable), and 11 of the 12 warmest years have occurred in the last 12 years (1995 to 2006). Warming, particularly since the 1970s, has generally been greater over land than over the oceans. Seasonally, warming has been slightly greater in the winter hemisphere. Additional warming occurs in cities and urban areas (often referred to as the urban heat island effect), but is confined in spatial extent, and its effects are allowed for both by excluding as many of the affected sites as possible from the global temperature data and by increasing the error range (the blue band in the figure).

A few areas have cooled since 1901, most notably the northern North Atlantic near southern Greenland. Warming during this time has been strongest over the continental interiors of Asia and northern North America. However, as these are areas with large year-to-year variability, the most evident warming signal has occurred in parts of the middle and lower latitudes, particularly the tropical oceans. In the lower left panel of Figure 1, which shows temperature trends since 1979, the pattern in the Pacific Ocean features warming and cooling regions related to El Niño.

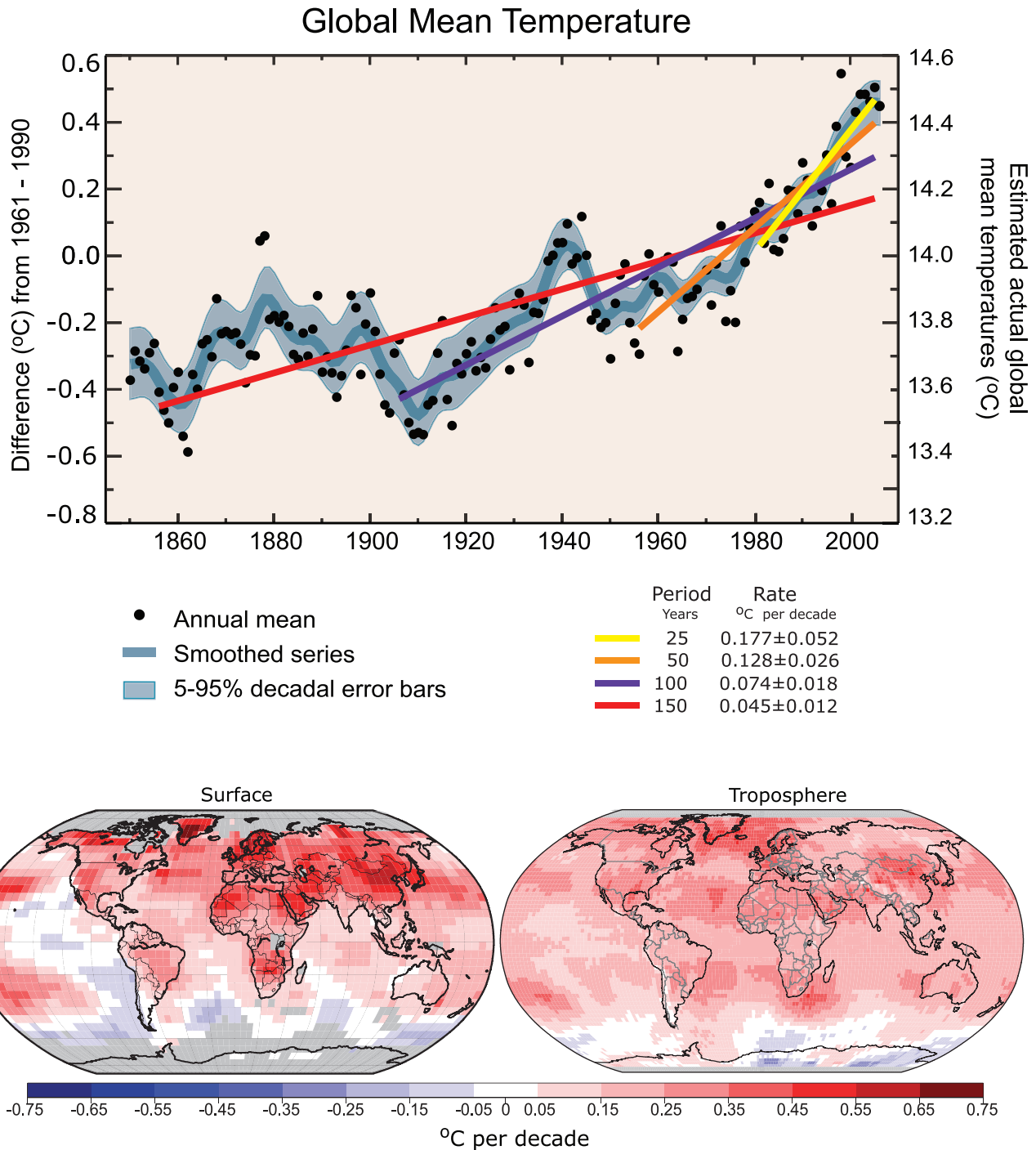
Analysis of long-term changes in daily temperature extremes has recently become possible for many regions of the world (parts of North America and southern South America, Europe, northern and eastern Asia, southern Africa and Australasia). Especially since the 1950s, these records show a decrease in the number of very cold days and nights and an increase in the number of extremely hot days and warm nights (see FAQ 3.3). The length of the frost-free season has increased in most mid- and high-latitude regions of both hemispheres. In the Northern Hemisphere, this is mostly manifest as an earlier start to spring.

In addition to the surface data described above, measurements of temperature above the surface have been made with weather balloons, with reasonable coverage over land since 1958, and from satellite data since 1979. All data are adjusted for changes in instruments and observing practices where necessary. Microwave satellite data have been used to create a 'satellite temperature record' for thick layers of the atmosphere including the troposphere (from the surface up to about 10 km) and the lower stratosphere (about 10 to 30 km). Despite several new analyses with improved cross-calibration of the 13 instruments on different satellites used since 1979 and compensation for changes in observing time and satellite altitude, some uncertainties remain in trends.

For global observations since the late 1950s, the most recent versions of all available data sets show that the troposphere has warmed at a slightly greater rate than the surface, while the stratosphere has cooled markedly since 1979. This is in accord with physical expectations and most model results, which demonstrate the role of increasing greenhouse gases in tropospheric warming and stratospheric cooling; ozone depletion also contributes substantially to stratospheric cooling.

Consistent with observed increases in surface temperature, there have been decreases in the length of river and lake ice seasons. Further, there has been an almost worldwide reduction in glacial mass and extent in the 20th century; melting of the Greenland Ice Sheet has recently become apparent; snow cover has decreased in many Northern Hemisphere regions; sea ice thickness and extent have decreased in the Arctic in all seasons, most dramatically in spring and summer; the oceans are warming; and sea level is rising due to thermal expansion of the oceans and melting of land ice.

*(continued)*



**FAQ 3.1, Figure 1.** (Top) Annual global mean observed temperatures<sup>1</sup> (black dots) along with simple fits to the data. The left hand axis shows anomalies relative to the 1961 to 1990 average and the right hand axis shows the estimated actual temperature (°C). Linear trend fits to the last 25 (yellow), 50 (orange), 100 (purple) and 150 years (red) are shown, and correspond to 1981 to 2005, 1956 to 2005, 1906 to 2005, and 1856 to 2005, respectively. Note that for shorter recent periods, the slope is greater, indicating accelerated warming. The blue curve is a smoothed depiction to capture the decadal variations. To give an idea of whether the fluctuations are meaningful, decadal 5% to 95% (light blue) error ranges about that line are given (accordingly, annual values do exceed those limits). Results from climate models driven by estimated radiative forcings for the 20th century (Chapter 9) suggest that there was little change prior to about 1915, and that a substantial fraction of the early 20th-century change was contributed by naturally occurring influences including solar radiation changes, volcanism and natural variability. From about 1940 to 1970 the increasing industrialisation following World War II increased pollution in the Northern Hemisphere, contributing to cooling, and increases in carbon dioxide and other greenhouse gases dominate the observed warming after the mid-1970s. (Bottom) Patterns of linear global temperature trends from 1979 to 2005 estimated at the surface (left), and for the troposphere (right) from the surface to about 10 km altitude, from satellite records. Grey areas indicate incomplete data. Note the more spatially uniform warming in the satellite tropospheric record while the surface temperature changes more clearly relate to land and ocean.

<sup>1</sup> From the HadCRUT3 data set.

## Frequently Asked Question 3.2

### How is Precipitation Changing?

*Observations show that changes are occurring in the amount, intensity, frequency and type of precipitation. These aspects of precipitation generally exhibit large natural variability, and El Niño and changes in atmospheric circulation patterns such as the North Atlantic Oscillation have a substantial influence. Pronounced long-term trends from 1900 to 2005 have been observed in precipitation amount in some places: significantly wetter in eastern North and South America, northern Europe and northern and central Asia, but drier in the Sahel, southern Africa, the Mediterranean and southern Asia. More precipitation now falls as rain rather than snow in northern regions. Widespread increases in heavy precipitation events have been observed, even in places where total amounts have decreased. These changes are associated with increased water vapour in the atmosphere arising from the warming of the world's oceans, especially at lower latitudes. There are also increases in some regions in the occurrences of both droughts and floods.*

Precipitation is the general term for rainfall, snowfall and other forms of frozen or liquid water falling from clouds. Precipitation is intermittent, and the character of the precipitation when it occurs depends greatly on temperature and the weather situation. The latter determines the supply of moisture through winds and surface evaporation, and how it is gathered together in storms as clouds. Precipitation forms as water vapour condenses, usually in rising air that expands and hence cools. The upward motion comes from air rising over mountains, warm air riding over cooler air (warm front), colder air pushing under warmer air (cold front), convection from local heating of the surface, and other weather and cloud systems. Hence, changes in any of these aspects alter precipitation. As precipitation maps tend to be spotty, overall trends in precipitation are indicated by the Palmer Drought Severity Index (see Figure 1), which is a measure of soil moisture using precipitation and crude estimates of changes in evaporation.

A consequence of increased heating from the human-induced enhanced greenhouse effect is increased evaporation, provided that adequate surface moisture is available (as it always is over the oceans and other wet surfaces). Hence, surface moisture effectively acts as an 'air conditioner', as heat used for evaporation acts to moisten the air rather than warm it. An observed consequence of this is that summers often tend to be either warm and dry or cool and wet. In the areas of eastern North and South America where it has become wetter (Figure 1), temperatures have therefore increased less than elsewhere (see FAQ 3.3, Figure 1 for changes in warm days). Over northern continents in winter, however, more precipitation is associated with higher temperatures, as the water holding capacity of the atmosphere increases in the warmer conditions. However, in these regions, where precipitation has generally increased somewhat, increases in temperatures (FAQ 3.1) have increased drying, making the precipitation changes less evident in Figure 1.

As climate changes, several direct influences alter precipitation amount, intensity, frequency and type. Warming accelerates land surface drying and increases the potential incidence and severity of droughts, which has been observed in many places worldwide (Figure 1). However, a well-established physical law (the Clausius-Clapeyron relation) determines that the water-holding capacity of the atmosphere increases by about 7% for every 1°C rise in temperature. Observations of trends in relative humidity are uncertain but suggest that it has remained about the same overall, from the surface throughout the troposphere, and hence increased temperatures will have resulted in increased water vapour. Over the 20th century, based on changes in sea surface temperatures, it is estimated that atmospheric water vapour increased by about 5% in the atmosphere over the oceans. Because precipitation comes mainly from weather systems that feed on the water vapour stored in the atmosphere, this has generally increased precipitation intensity and the risk of heavy rain and snow events. Basic theory, climate model simulations and empirical evidence all confirm that warmer climates, owing to increased water vapour, lead to more intense precipitation events even when the total annual precipitation is reduced slightly, and with prospects for even stronger events when the overall precipitation amounts increase. The warmer climate therefore increases risks of both drought – where it is not raining – and floods – where it is – but at different times and/or places. For instance, the summer of 2002 in Europe brought widespread floods but was followed a year later in 2003 by record-breaking heat waves and drought. The distribution and timing of floods and droughts is most profoundly affected by the cycle of El Niño events, particularly in the tropics and over much of the mid-latitudes of Pacific-rim countries.

In areas where aerosol pollution masks the ground from direct sunlight, decreases in evaporation reduce the overall moisture supply to the atmosphere. Hence, even as the potential for heavier precipitation results from increased water vapour amounts, the duration and frequency of events may be curtailed, as it takes longer to recharge the atmosphere with water vapour.

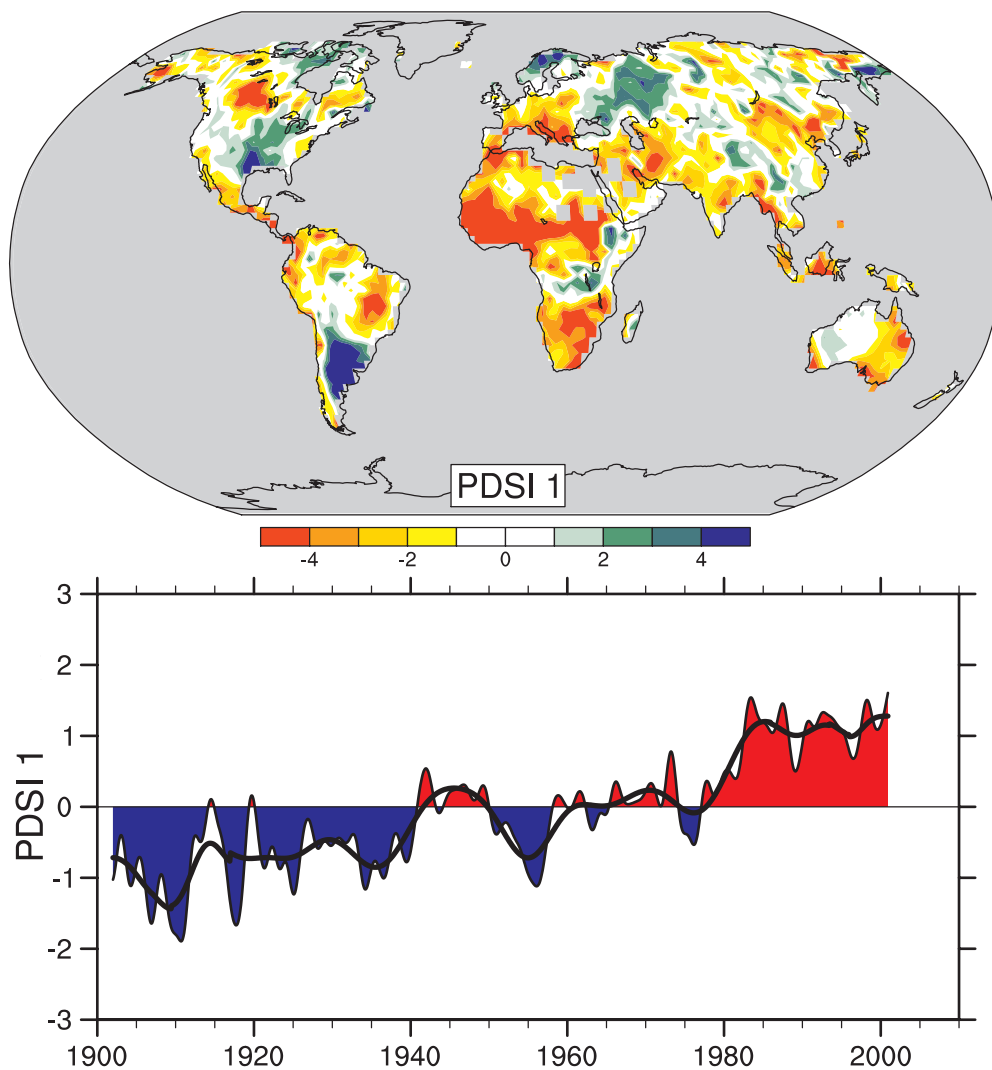
Local and regional changes in the character of precipitation also depend a great deal on atmospheric circulation patterns determined by El Niño, the North Atlantic Oscillation (NAO; a measure of westerly wind strength over the North Atlantic in winter) and other patterns of variability. Some of these observed circulation changes are associated with climate change. An associated shift in the storm track makes some regions wetter and some – often nearby – drier, making for complex patterns of change. For instance, in the European sector a more positive NAO in the 1990s led to wetter conditions in northern Europe and drier conditions over the Mediterranean and northern African regions (Figure 1). The prolonged drought in the Sahel (see Figure 1), which was pronounced from the late 1960s to the late 1980s,

*(continued)*

continues although it is not quite as intense as it was; it has been linked, through changes in atmospheric circulation, to changes in tropical sea surface temperature patterns in the Pacific, Indian and Atlantic Basins. Drought has become widespread throughout much of Africa and more common in the tropics and subtropics.

As temperatures rise, the likelihood of precipitation falling as rain rather than snow increases, especially in autumn and spring at the beginning and end of the snow season, and in areas where temperatures are near freezing. Such changes are observed in many places, especially over land in middle and high latitudes of

the Northern Hemisphere, leading to increased rains but reduced snowpacks, and consequently diminished water resources in summer, when they are most needed. Nevertheless, the often spotty and intermittent nature of precipitation means observed patterns of change are complex. The long-term record emphasizes that patterns of precipitation vary somewhat from year to year, and even prolonged multi-year droughts are usually punctuated by a year of heavy rains; for instance as El Niño influences are felt. An example may be the wet winter of 2004–2005 in the southwestern USA following a six-year drought and below-normal snowpack.



**FAQ 3.2, Figure 1.** The most important spatial pattern (top) of the monthly Palmer Drought Severity Index (PDSI) for 1900 to 2002. The PDSI is a prominent index of drought and measures the cumulative deficit (relative to local mean conditions) in surface land moisture by incorporating previous precipitation and estimates of moisture drawn into the atmosphere (based on atmospheric temperatures) into a hydrological accounting system. The lower panel shows how the sign and strength of this pattern has changed since 1900. Red and orange areas are drier (wetter) than average and blue and green areas are wetter (drier) than average when the values shown in the lower plot are positive (negative). The smooth black curve shows decadal variations. The time series approximately corresponds to a trend, and this pattern and its variations account for 67% of the linear trend of PDSI from 1900 to 2002 over the global land area. It therefore features widespread increasing African drought, especially in the Sahel, for instance. Note also the wetter areas, especially in eastern North and South America and northern Eurasia. Adapted from Dai et al. (2004b).



### Frequently Asked Question 3.3

## Has there been a Change in Extreme Events like Heat Waves, Droughts, Floods and Hurricanes?

*Since 1950, the number of heat waves has increased and widespread increases have occurred in the numbers of warm nights. The extent of regions affected by droughts has also increased as precipitation over land has marginally decreased while evaporation has increased due to warmer conditions. Generally, numbers of heavy daily precipitation events that lead to flooding have increased, but not everywhere. Tropical storm and hurricane frequencies vary considerably from year to year, but evidence suggests substantial increases in intensity and duration since the 1970s. In the extratropics, variations in tracks and intensity of storms reflect variations in major features of the atmospheric circulation, such as the North Atlantic Oscillation.*

In several regions of the world, indications of changes in various types of extreme climate events have been found. The extremes are commonly considered to be the values exceeded 1, 5 and 10% of the time (at one extreme) or 90, 95 and 99% of the time (at the other extreme). The warm nights or hot days (discussed below) are those exceeding the 90th percentile of temperature, while cold nights or days are those falling below the 10th percentile. Heavy precipitation is defined as daily amounts greater than the 95th (or for 'very heavy', the 99th) percentile.

In the last 50 years for the land areas sampled, there has been a significant decrease in the annual occurrence of cold nights and a significant increase in the annual occurrence of warm nights (Figure 1). Decreases in the occurrence of cold days and increases in hot days, while widespread, are generally less marked. The distributions of minimum and maximum temperatures have not only shifted to higher values, consistent with overall warming, but the cold extremes have warmed more than the warm extremes over the last 50 years (Figure 1). More warm extremes imply an increased frequency of heat waves. Further supporting indications include the observed trend towards fewer frost days associated with the average warming in most mid-latitude regions.

A prominent indication of a change in extremes is the observed evidence of increases in heavy precipitation events over the mid-latitudes in the last 50 years, even in places where mean precipitation amounts are not increasing (see also FAQ 3.2). For very heavy precipitation events, increasing trends are reported as well, but results are available for few areas.

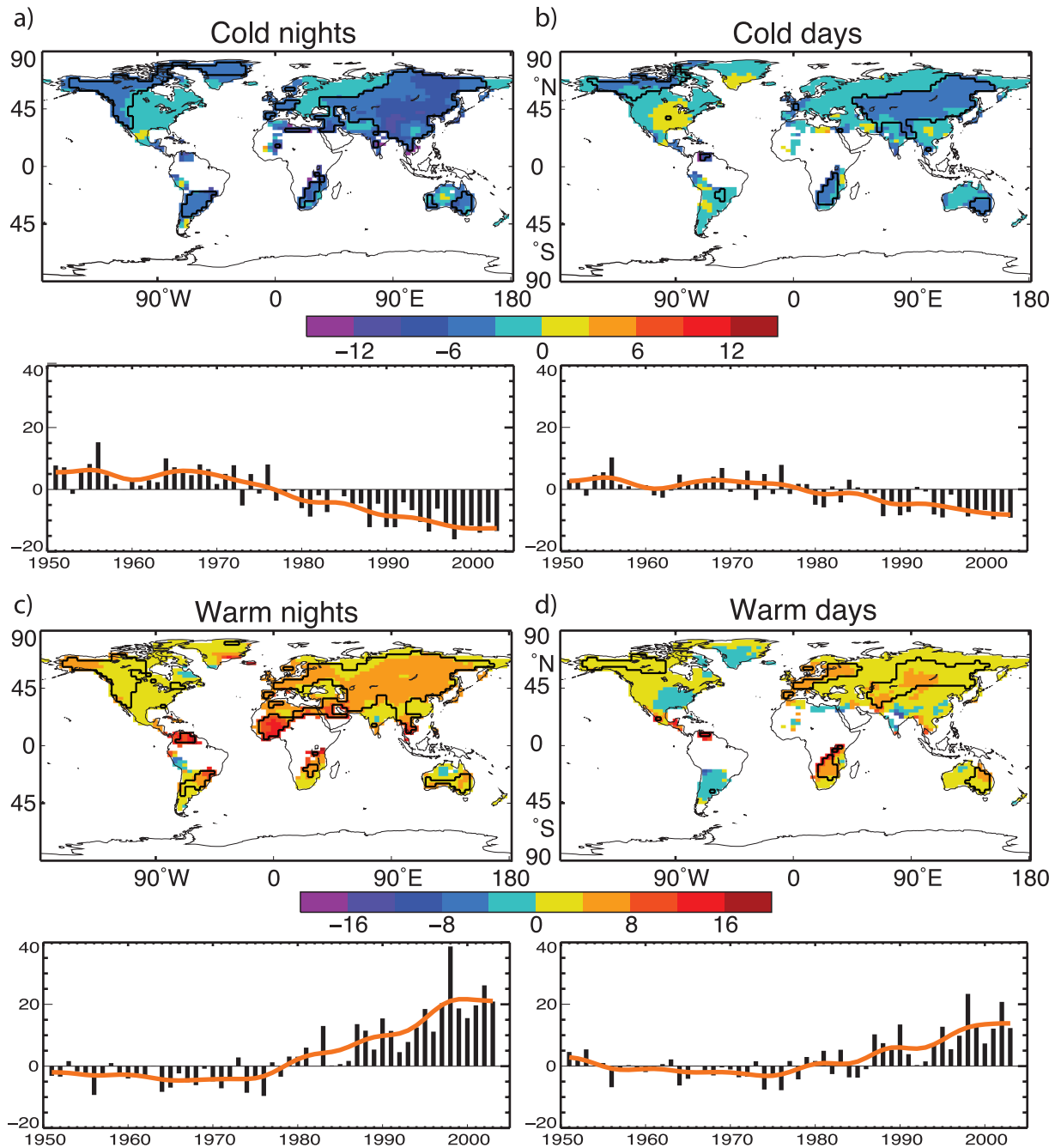
Drought is easier to measure because of its long duration. While there are numerous indices and metrics of drought, many studies use monthly precipitation totals and temperature averages combined into a measure called the Palmer Drought Severity Index (PDSI). The PDSI calculated from the middle of the 20th century shows a large drying trend over many Northern Hemisphere land areas since the mid-1950s, with widespread drying over much of southern Eurasia, northern Africa, Canada and Alaska

(FAQ 3.2, Figure 1), and an opposite trend in eastern North and South America. In the Southern Hemisphere, land surfaces were wet in the 1970s and relatively dry in the 1960s and 1990s, and there was a drying trend from 1974 to 1998. Longer-duration records for Europe for the whole of the 20th century indicate few significant trends. Decreases in precipitation over land since the 1950s are the likely main cause for the drying trends, although large surface warming during the last two to three decades has also likely contributed to the drying. One study shows that very dry land areas across the globe (defined as areas with a PDSI of less than -3.0) have more than doubled in extent since the 1970s, associated with an initial precipitation decrease over land related to the El Niño-Southern Oscillation and with subsequent increases primarily due to surface warming.

Changes in tropical storm and hurricane frequency and intensity are masked by large natural variability. The El Niño-Southern Oscillation greatly affects the location and activity of tropical storms around the world. Globally, estimates of the potential destructiveness of hurricanes show a substantial upward trend since the mid-1970s, with a trend towards longer storm duration and greater storm intensity, and the activity is strongly correlated with tropical sea surface temperature. These relationships have been reinforced by findings of a large increase in numbers and proportion of strong hurricanes globally since 1970 even as total numbers of cyclones and cyclone days decreased slightly in most basins. Specifically, the number of category 4 and 5 hurricanes increased by about 75% since 1970. The largest increases were in the North Pacific, Indian and Southwest Pacific Oceans. However, numbers of hurricanes in the North Atlantic have also been above normal in 9 of the last 11 years, culminating in the record-breaking 2005 season.

Based on a variety of measures at the surface and in the upper troposphere, it is likely that there has been a poleward shift as well as an increase in Northern Hemisphere winter storm track activity over the second half of the 20th century. These changes are part of variations that have occurred related to the North Atlantic Oscillation. Observations from 1979 to the mid-1990s reveal a tendency towards a stronger December to February circumpolar westerly atmospheric circulation throughout the troposphere and lower stratosphere, together with poleward displacements of jet streams and increased storm track activity. Observational evidence for changes in small-scale severe weather phenomena (such as tornadoes, hail and thunderstorms) is mostly local and too scattered to draw general conclusions; increases in many areas arise because of increased public awareness and improved efforts to collect reports of these phenomena.

*(continued)*



**FAQ 3.3, Figure 1.** Observed trends (days per decade) for 1951 to 2003 in the frequency of extreme temperatures, defined based on 1961 to 1990 values, as maps for the 10th percentile: (a) cold nights and (b) cold days; and 90th percentile: (c) warm nights and (d) warm days. Trends were calculated only for grid boxes that had at least 40 years of data during this period and had data until at least 1999. Black lines enclose regions where trends are significant at the 5% level. Below each map are the global annual time series of anomalies (with respect to 1961 to 1990). The orange line shows decadal variations. Trends are significant at the 5% level for all the global indices shown. Adapted from Alexander et al. (2006).



## Frequently Asked Question 4.1

## Is the Amount of Snow and Ice on the Earth Decreasing?

Yes. Observations show a global-scale decline of snow and ice over many years, especially since 1980 and increasing during the past decade, despite growth in some places and little change in others (Figure 1). Most mountain glaciers are getting smaller. Snow cover is retreating earlier in the spring. Sea ice in the Arctic is shrinking in all seasons, most dramatically in summer. Reductions are reported in permafrost, seasonally frozen ground and river and lake ice. Important coastal regions of the ice sheets on Greenland and West Antarctica, and the glaciers of the Antarctic Peninsula, are thinning and contributing to sea level rise. The total contribution of glacier, ice cap and ice sheet melt to sea level rise is estimated as  $1.2 \pm 0.4 \text{ mm yr}^{-1}$  for the period 1993 to 2003.

Continuous satellite measurements capture most of the Earth's seasonal snow cover on land, and reveal that Northern Hemisphere spring snow cover has declined by about 2% per decade since 1966, although there is little change in autumn or early winter. In many places, the spring decrease has occurred despite increases in precipitation.

Satellite data do not yet allow similarly reliable measurement of ice conditions on lakes and rivers, or in seasonally or permanently frozen ground. However, numerous local and regional reports have been published, and generally seem to indicate warming of permafrost, an increase in thickness of the summer thawed layer over permafrost, a decrease in winter freeze depth in seasonally frozen areas, a decrease in areal extent of permafrost and a decrease in duration of seasonal river and lake ice.

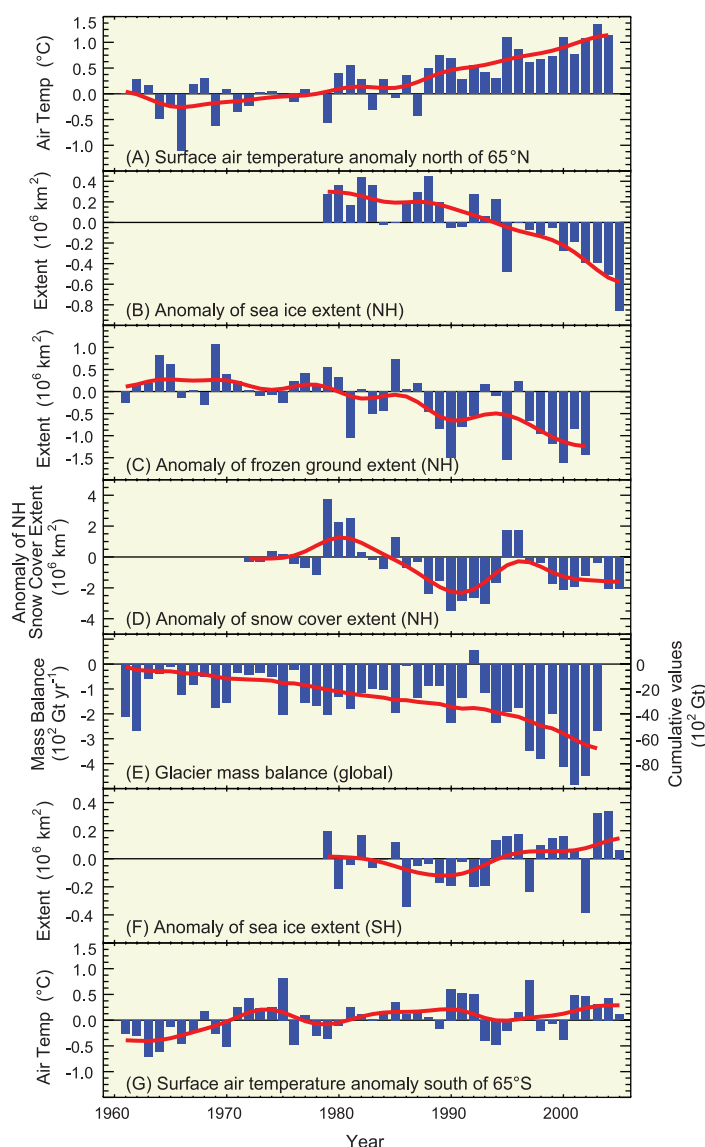
Since 1978, satellite data have provided continuous coverage of sea ice extent in both polar regions. For the Arctic, average annual sea ice extent has decreased by  $2.7 \pm 0.6\%$  per decade, while summer sea ice extent has decreased by  $7.4 \pm 2.4\%$  per decade. The antarctic sea ice extent exhibits no significant trend. Thickness data, especially from submarines, are available but restricted to the central Arctic, where they indicate thinning of approximately 40% between the period 1958 to 1977 and the 1990s. This is likely an overestimate of the thinning over the entire arctic region however.

Most mountain glaciers and ice caps have been shrinking, with the retreat probably having started about 1850. Although many Northern Hemisphere glaciers had a few years of near-balance around 1970, this was followed by increased shrinkage. Melting of glaciers and ice caps contributed  $0.77 \pm 0.22 \text{ mm yr}^{-1}$  to sea level rise between 1991 and 2004

Taken together, the ice sheets of Greenland and Antarctica are very likely shrinking, with Greenland contributing about  $0.2 \pm 0.1 \text{ mm yr}^{-1}$  and Antarctica contributing  $0.2 \pm 0.35 \text{ mm yr}^{-1}$  to sea level rise over the period 1993 to 2003. There is evidence of accelerated loss through 2005. Thickening of high-altitude, cold regions of Greenland and East Antarctica, perhaps from increased snowfall, has been more than offset by thinning in

coastal regions of Greenland and West Antarctica in response to increased ice outflow and increased Greenland surface melting.

Ice interacts with the surrounding climate in complex ways, so the causes of specific changes are not always clear. Nonetheless, it is an unavoidable fact that ice melts when the local temperature is  
(continued)



**FAQ 4.1, Figure 1.** Anomaly time series (departure from the long-term mean) of polar surface air temperature (A, G), arctic and antarctic sea ice extent (B, F), Northern Hemisphere (NH) frozen ground extent (C), NH snow cover extent (D) and global glacier mass balance (E). The solid red line in E denotes the cumulative global glacier mass balance; in the other panels it shows decadal variations (see Appendix 3.A).

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above the freezing point. Reductions in snow cover and in mountain glaciers have occurred despite increased snowfall in many cases, implicating increased air temperatures. Similarly, although snow cover changes affect frozen ground and lake and river ice, this does not seem sufficient to explain the observed changes, suggesting that increased local air temperatures have been important. Observed arctic sea ice reductions can be simulated fairly well in

models driven by historical circulation and temperature changes. The observed increases in snowfall on ice sheets in some cold central regions, surface melting in coastal regions and sub-ice-shelf melting along many coasts are all consistent with warming. The geographically widespread nature of these snow and ice changes suggests that widespread warming is the cause of the Earth's overall loss of ice.

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## Frequently Asked Question 5.1

### Is Sea Level Rising?

*Yes, there is strong evidence that global sea level gradually rose in the 20th century and is currently rising at an increased rate, after a period of little change between AD 0 and AD 1900. Sea level is projected to rise at an even greater rate in this century. The two major causes of global sea level rise are thermal expansion of the oceans (water expands as it warms) and the loss of land-based ice due to increased melting.*

Global sea level rose by about 120 m during the several millennia that followed the end of the last ice age (approximately 21,000 years ago), and stabilised between 3,000 and 2,000 years ago. Sea level indicators suggest that global sea level did not change significantly from then until the late 19th century. The instrumental record of modern sea level change shows evidence for onset of sea level rise during the 19th century. Estimates for the 20th century show that global average sea level rose at a rate of about  $1.7 \text{ mm yr}^{-1}$ .

Satellite observations available since the early 1990s provide more accurate sea level data with nearly global coverage. This decade-long satellite altimetry data set shows that since 1993, sea level has been rising at a rate of around  $3 \text{ mm yr}^{-1}$ , significantly higher than the average during the previous half century. Coastal tide gauge measurements confirm this observation, and indicate that similar rates have occurred in some earlier decades.

In agreement with climate models, satellite data and hydrographic observations show that sea level is not rising uniformly around the world. In some regions, rates are up to several times the global mean rise, while in other regions sea level is falling. Substantial spatial variation in rates of sea level change is also inferred from hydrographic observations. Spatial variability of the rates of sea level rise is mostly due to non-uniform changes in temperature and salinity and related to changes in the ocean circulation.

Near-global ocean temperature data sets made available in recent years allow a direct calculation of thermal expansion. It is believed that on average, over the period from 1961 to 2003, thermal expansion contributed about one-quarter of the observed sea level rise, while melting of land ice accounted for less than half. Thus, the full magnitude of the observed sea level rise during that period was not satisfactorily explained by those data sets, as reported in the IPCC Third Assessment Report.

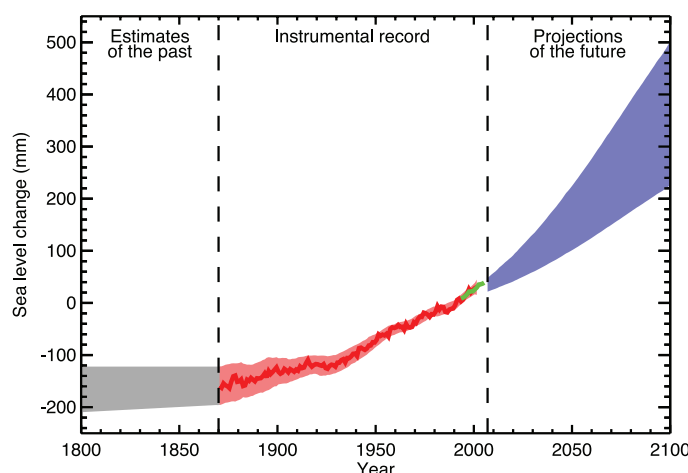
During recent years (1993–2003), for which the observing system is much better, thermal expansion and melting of land ice each account for about half of the observed sea level rise, although there is some uncertainty in the estimates.

The reasonable agreement in recent years between the observed rate of sea level rise and the sum of thermal expansion and loss of land ice suggests an upper limit for the magnitude of change in land-based water storage, which is relatively poorly known. Model results suggest no net trend in the storage of water over land due to climate-driven changes but there are large interannual and decadal fluctuations. However, for the recent period 1993 to 2003,

the small discrepancy between observed sea level rise and the sum of known contributions might be due to unquantified human-induced processes (e.g., groundwater extraction, impoundment in reservoirs, wetland drainage and deforestation).

Global sea level is projected to rise during the 21st century at a greater rate than during 1961 to 2003. Under the IPCC Special Report on Emission Scenarios (SRES) A1B scenario by the mid-2090s, for instance, global sea level reaches 0.22 to 0.44 m above 1990 levels, and is rising at about  $4 \text{ mm yr}^{-1}$ . As in the past, sea level change in the future will not be geographically uniform, with regional sea level change varying within about  $\pm 0.15 \text{ m}$  of the mean in a typical model projection. Thermal expansion is projected to contribute more than half of the average rise, but land ice will lose mass increasingly rapidly as the century progresses. An important uncertainty relates to whether discharge of ice from the ice sheets will continue to increase as a consequence of accelerated ice flow, as has been observed in recent years. This would add to the amount of sea level rise, but quantitative projections of how much it would add cannot be made with confidence, owing to limited understanding of the relevant processes.

Figure 1 shows the evolution of global mean sea level in the past and as projected for the 21st century for the SRES A1B scenario.



**FAQ 5.1, Figure 1.** Time series of global mean sea level (deviation from the 1980–1999 mean) in the past and as projected for the future. For the period before 1870, global measurements of sea level are not available. The grey shading shows the uncertainty in the estimated long-term rate of sea level change (Section 6.4.3). The red line is a reconstruction of global mean sea level from tide gauges (Section 5.5.2.1), and the red shading denotes the range of variations from a smooth curve. The green line shows global mean sea level observed from satellite altimetry. The blue shading represents the range of model projections for the SRES A1B scenario for the 21st century, relative to the 1980 to 1999 mean, and has been calculated independently from the observations. Beyond 2100, the projections are increasingly dependent on the emissions scenario (see Chapter 10 for a discussion of sea level rise projections for other scenarios considered in this report). Over many centuries or millennia, sea level could rise by several metres (Section 10.7.4).

## Frequently Asked Question 6.1

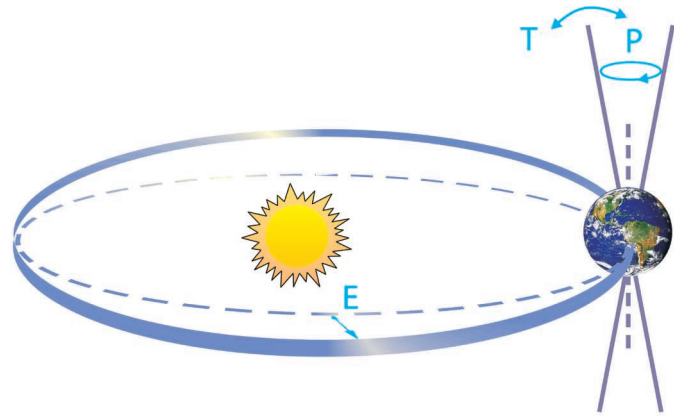
# What Caused the Ice Ages and Other Important Climate Changes Before the Industrial Era?

Climate on Earth has changed on all time scales, including long before human activity could have played a role. Great progress has been made in understanding the causes and mechanisms of these climate changes. Changes in Earth's radiation balance were the principal driver of past climate changes, but the causes of such changes are varied. For each case – be it the Ice Ages, the warmth at the time of the dinosaurs or the fluctuations of the past millennium – the specific causes must be established individually. In many cases, this can now be done with good confidence, and many past climate changes can be reproduced with quantitative models.

Global climate is determined by the radiation balance of the planet (see FAQ 1.1). There are three fundamental ways the Earth's radiation balance can change, thereby causing a climate change: (1) changing the incoming solar radiation (e.g., by changes in the Earth's orbit or in the Sun itself), (2) changing the fraction of solar radiation that is reflected (this fraction is called the albedo – it can be changed, for example, by changes in cloud cover, small particles called aerosols or land cover), and (3) altering the long-wave energy radiated back to space (e.g., by changes in greenhouse gas concentrations). In addition, local climate also depends on how heat is distributed by winds and ocean currents. All of these factors have played a role in past climate changes.

Starting with the ice ages that have come and gone in regular cycles for the past nearly three million years, there is strong evidence that these are linked to regular variations in the Earth's orbit around the Sun, the so-called Milankovitch cycles (Figure 1). These cycles change the amount of solar radiation received at each latitude in each season (but hardly affect the global annual mean), and they can be calculated with astronomical precision. There is still some discussion about how exactly this starts and ends ice ages, but many studies suggest that the amount of summer sunshine on northern continents is crucial: if it drops below a critical value, snow from the past winter does not melt away in summer and an ice sheet starts to grow as more and more snow accumulates. Climate model simulations confirm that an Ice Age can indeed be started in this way, while simple conceptual models have been used to successfully 'hindcast' the onset of past glaciations based on the orbital changes. The next large reduction in northern summer insolation, similar to those that started past Ice Ages, is due to begin in 30,000 years.

Although it is not their primary cause, atmospheric carbon dioxide ( $\text{CO}_2$ ) also plays an important role in the ice ages. Antarctic ice core data show that  $\text{CO}_2$  concentration is low in the cold glacial times (~190 ppm), and high in the warm interglacials (~280 ppm); atmospheric  $\text{CO}_2$  follows temperature changes in Antarctica with a lag of some hundreds of years. Because the climate changes at the beginning and end of ice ages take several thousand years,



**FAQ 6.1, Figure 1.** Schematic of the Earth's orbital changes (Milankovitch cycles) that drive the ice age cycles. 'T' denotes changes in the tilt (or obliquity) of the Earth's axis, 'E' denotes changes in the eccentricity of the orbit (due to variations in the minor axis of the ellipse), and 'P' denotes precession, that is, changes in the direction of the axis tilt at a given point of the orbit. Source: Rahmstorf and Schellnhuber (2006).

most of these changes are affected by a positive  $\text{CO}_2$  feedback; that is, a small initial cooling due to the Milankovitch cycles is subsequently amplified as the  $\text{CO}_2$  concentration falls. Model simulations of ice age climate (see discussion in Section 6.4.1) yield realistic results only if the role of  $\text{CO}_2$  is accounted for.

During the last ice age, over 20 abrupt and dramatic climate shifts occurred that are particularly prominent in records around the northern Atlantic (see Section 6.4). These differ from the glacial-interglacial cycles in that they probably do not involve large changes in global mean temperature: changes are not synchronous in Greenland and Antarctica, and they are in the opposite direction in the South and North Atlantic. This means that a major change in global radiation balance would not have been needed to cause these shifts; a redistribution of heat within the climate system would have sufficed. There is indeed strong evidence that changes in ocean circulation and heat transport can explain many features of these abrupt events; sediment data and model simulations show that some of these changes could have been triggered by instabilities in the ice sheets surrounding the Atlantic at the time, and the associated freshwater release into the ocean.

Much warmer times have also occurred in climate history – during most of the past 500 million years, Earth was probably completely free of ice sheets (geologists can tell from the marks ice leaves on rock), unlike today, when Greenland and Antarctica are ice-covered. Data on greenhouse gas abundances going back beyond a million years, that is, beyond the reach of antarctic ice cores, are still rather uncertain, but analysis of geological

(continued)

samples suggests that the warm ice-free periods coincide with high atmospheric CO<sub>2</sub> levels. On million-year time scales, CO<sub>2</sub> levels change due to tectonic activity, which affects the rates of CO<sub>2</sub> exchange of ocean and atmosphere with the solid Earth. See Section 6.3 for more about these ancient climates.

Another likely cause of past climatic changes is variations in the energy output of the Sun. Measurements over recent decades show that the solar output varies slightly (by close to 0.1%) in an 11-year cycle. Sunspot observations (going back to the 17th century), as well as data from isotopes generated by cosmic radiation, provide evidence for longer-term changes in solar activity. Data correlation and model simulations indicate that solar variability

and volcanic activity are likely to be leading reasons for climate variations during the past millennium, before the start of the industrial era.

These examples illustrate that different climate changes in the past had different causes. The fact that natural factors caused climate changes in the past does not mean that the current climate change is natural. By analogy, the fact that forest fires have long been caused naturally by lightning strikes does not mean that fires cannot also be caused by a careless camper. FAQ 2.1 addresses the question of how human influences compare with natural ones in their contributions to recent climate change.

## Frequently Asked Question 6.2

# Is the Current Climate Change Unusual Compared to Earlier Changes in Earth's History?

*Climate has changed on all time scales throughout Earth's history. Some aspects of the current climate change are not unusual, but others are. The concentration of CO<sub>2</sub> in the atmosphere has reached a record high relative to more than the past half-million years, and has done so at an exceptionally fast rate. Current global temperatures are warmer than they have ever been during at least the past five centuries, probably even for more than a millennium. If warming continues unabated, the resulting climate change within this century would be extremely unusual in geological terms. Another unusual aspect of recent climate change is its cause: past climate changes were natural in origin (see FAQ 6.1), whereas most of the warming of the past 50 years is attributable to human activities.*

When comparing the current climate change to earlier, natural ones, three distinctions must be made. First, it must be clear which variable is being compared: is it greenhouse gas concentration or temperature (or some other climate parameter), and is it their absolute value or their rate of change? Second, local changes must not be confused with global changes. Local climate changes are often much larger than global ones, since local factors (e.g., changes in oceanic or atmospheric circulation) can shift the delivery of heat or moisture from one place to another and local feedbacks operate (e.g., sea ice feedback). Large changes in global mean temperature, in contrast, require some global forcing (such as a change in greenhouse gas concentration or solar activity). Third, it is necessary to distinguish between time scales. Climate changes over millions of years can be much larger and have different causes (e.g., continental drift) compared to climate changes on a centennial time scale.

The main reason for the current concern about climate change is the rise in atmospheric carbon dioxide (CO<sub>2</sub>) concentration (and some other greenhouse gases), which is very unusual for the Quaternary (about the last two million years). The concentration of CO<sub>2</sub> is now known accurately for the past 650,000 years from antarctic ice cores. During this time, CO<sub>2</sub> concentration varied between a low of 180 ppm during cold glacial times and a high of 300 ppm during warm interglacials. Over the past century, it rapidly increased well out of this range, and is now 379 ppm (see Chapter 2). For comparison, the approximately 80-ppm rise in CO<sub>2</sub> concentration at the end of the past ice ages generally took over 5,000 years. Higher values than at present have only occurred many millions of years ago (see FAQ 6.1).

Temperature is a more difficult variable to reconstruct than CO<sub>2</sub> (a globally well-mixed gas), as it does not have the same value all over the globe, so that a single record (e.g., an ice core) is only of limited value. Local temperature fluctuations, even those over just a few decades, can be several degrees celsius, which is larger than the global warming signal of the past century of about 0.7°C.

More meaningful for global changes is an analysis of large-scale (global or hemispheric) averages, where much of the local varia-

tion averages out and variability is smaller. Sufficient coverage of instrumental records goes back only about 150 years. Further back in time, compilations of proxy data from tree rings, ice cores, etc., go back more than a thousand years with decreasing spatial coverage for earlier periods (see Section 6.5). While there are differences among those reconstructions and significant uncertainties remain, all published reconstructions find that temperatures were warm during medieval times, cooled to low values in the 17th, 18th and 19th centuries, and warmed rapidly after that. The medieval level of warmth is uncertain, but may have been reached again in the mid-20th century, only to have likely been exceeded since then. These conclusions are supported by climate modelling as well. Before 2,000 years ago, temperature variations have not been systematically compiled into large-scale averages, but they do not provide evidence for warmer-than-present global annual mean temperatures going back through the Holocene (the last 11,600 years; see Section 6.4). There are strong indications that a warmer climate, with greatly reduced global ice cover and higher sea level, prevailed until around 3 million years ago. Hence, current warmth appears unusual in the context of the past millennia, but not unusual on longer time scales for which changes in tectonic activity (which can drive natural, slow variations in greenhouse gas concentration) become relevant (see Box 6.1).

A different matter is the current rate of warming. Are more rapid global climate changes recorded in proxy data? The largest temperature changes of the past million years are the glacial cycles, during which the global mean temperature changed by 4°C to 7°C between ice ages and warm interglacial periods (local changes were much larger, for example near the continental ice sheets). However, the data indicate that the global warming at the end of an ice age was a gradual process taking about 5,000 years (see Section 6.3). It is thus clear that the current rate of global climate change is much more rapid and very unusual in the context of past changes. The much-discussed abrupt climate shifts during glacial times (see Section 6.3) are not counter-examples, since they were probably due to changes in ocean heat transport, which would be unlikely to affect the global mean temperature.

Further back in time, beyond ice core data, the time resolution of sediment cores and other archives does not resolve changes as rapid as the present warming. Hence, although large climate changes have occurred in the past, there is no evidence that these took place at a faster rate than present warming. If projections of approximately 5°C warming in this century (the upper end of the range) are realised, then the Earth will have experienced about the same amount of global mean warming as it did at the end of the last ice age; there is no evidence that this rate of possible future global change was matched by any comparable global temperature increase of the last 50 million years.



## Frequently Asked Question 7.1

# Are the Increases in Atmospheric Carbon Dioxide and Other Greenhouse Gases During the Industrial Era Caused by Human Activities?

*Yes, the increases in atmospheric carbon dioxide (CO<sub>2</sub>) and other greenhouse gases during the industrial era are caused by human activities. In fact, the observed increase in atmospheric CO<sub>2</sub> concentrations does not reveal the full extent of human emissions in that it accounts for only 55% of the CO<sub>2</sub> released by human activity since 1959. The rest has been taken up by plants on land and by the oceans. In all cases, atmospheric concentrations of greenhouse gases, and their increases, are determined by the balance between sources (emissions of the gas from human activities and natural systems) and sinks (the removal of the gas from the atmosphere by conversion to a different chemical compound). Fossil fuel combustion (plus a smaller contribution from cement manufacture) is responsible for more than 75% of human-caused CO<sub>2</sub> emissions. Land use change (primarily deforestation) is responsible for the remainder. For methane, another important greenhouse gas, emissions generated by human activities exceeded natural emissions over the last 25 years. For nitrous oxide, emissions generated by human activities are equal to natural emissions to the atmosphere. Most of the long-lived halogen-containing gases (such as chlorofluorocarbons) are manufactured by humans, and were not present in the atmosphere before the industrial era. On average, present-day tropospheric ozone has increased 38% since pre-industrial times, and the increase results from atmospheric reactions of short-lived pollutants emitted by human activity. The concentration of CO<sub>2</sub> is now 379 parts per million (ppm) and methane is greater than 1,774 parts per billion (ppb), both very likely much higher than any time in at least 650 kyr (during which CO<sub>2</sub> remained between 180 and 300 ppm and methane between 320 and 790 ppb). The recent rate of change is dramatic and unprecedented; increases in CO<sub>2</sub> never exceeded 30 ppm in 1 kyr – yet now CO<sub>2</sub> has risen by 30 ppm in just the last 17 years.*

## Carbon Dioxide

Emissions of CO<sub>2</sub> (Figure 1a) from fossil fuel combustion, with contributions from cement manufacture, are responsible for more than 75% of the increase in atmospheric CO<sub>2</sub> concentration since pre-industrial times. The remainder of the increase comes from land use changes dominated by deforestation (and associated biomass burning) with contributions from changing agricultural practices. All these increases are caused by human activity. The natural carbon cycle cannot explain the observed atmospheric increase of 3.2 to 4.1 GtC yr<sup>-1</sup> in the form of CO<sub>2</sub> over the last 25 years. (One GtC equals 10<sup>15</sup> grams of carbon, i.e., one billion tonnes.)

Natural processes such as photosynthesis, respiration, decay and sea surface gas exchange lead to massive exchanges, sources and sinks of CO<sub>2</sub> between the land and atmosphere (estimated at

~120 GtC yr<sup>-1</sup>) and the ocean and atmosphere (estimated at ~90 GtC yr<sup>-1</sup>; see figure 7.3). The natural sinks of carbon produce a small net uptake of CO<sub>2</sub> of approximately 3.3 GtC yr<sup>-1</sup> over the last 15 years, partially offsetting the human-caused emissions. Were it not for the natural sinks taking up nearly half the human-produced CO<sub>2</sub> over the past 15 years, atmospheric concentrations would have grown even more dramatically.

The increase in atmospheric CO<sub>2</sub> concentration is known to be caused by human activities because the character of CO<sub>2</sub> in the atmosphere, in particular the ratio of its heavy to light carbon atoms, has changed in a way that can be attributed to addition of fossil fuel carbon. In addition, the ratio of oxygen to nitrogen in the atmosphere has declined as CO<sub>2</sub> has increased; this is as expected because oxygen is depleted when fossil fuels are burned. A heavy form of carbon, the carbon-13 isotope, is less abundant in vegetation and in fossil fuels that were formed from past vegetation, and is more abundant in carbon in the oceans and in volcanic or geothermal emissions. The relative amount of the carbon-13 isotope in the atmosphere has been declining, showing that the added carbon comes from fossil fuels and vegetation. Carbon also has a rare radioactive isotope, carbon-14, which is present in atmospheric CO<sub>2</sub> but absent in fossil fuels. Prior to atmospheric testing of nuclear weapons, decreases in the relative amount of carbon-14 showed that fossil fuel carbon was being added to the atmosphere.

## Halogen-Containing Gases

Human activities are responsible for the bulk of long-lived atmospheric halogen-containing gas concentrations. Before industrialisation, there were only a few naturally occurring halogen-containing gases, for example, methyl bromide and methyl chloride. The development of new techniques for chemical synthesis resulted in a proliferation of chemically manufactured halogen-containing gases during the last 50 years of the 20th century. Emissions of key halogen-containing gases produced by humans are shown in Figure 1b. Atmospheric lifetimes range from 45 to 100 years for the chlorofluorocarbons (CFCs) plotted here, from 1 to 18 years for the hydrochlorofluorocarbons (HCFCs), and from 1 to 270 years for the hydrofluorocarbons (HFCs). The perfluorocarbons (PFCs, not plotted) persist in the atmosphere for thousands of years. Concentrations of several important halogen-containing gases, including CFCs, are now stabilising or decreasing at the Earth's surface as a result of the Montreal Protocol on Substances that Deplete the Ozone Layer and its Amendments. Concentrations of HCFCs, production of which is to be phased out by 2030, and of the Kyoto Protocol gases HFCs and PFCs, are currently increasing. *(continued)*

## Methane

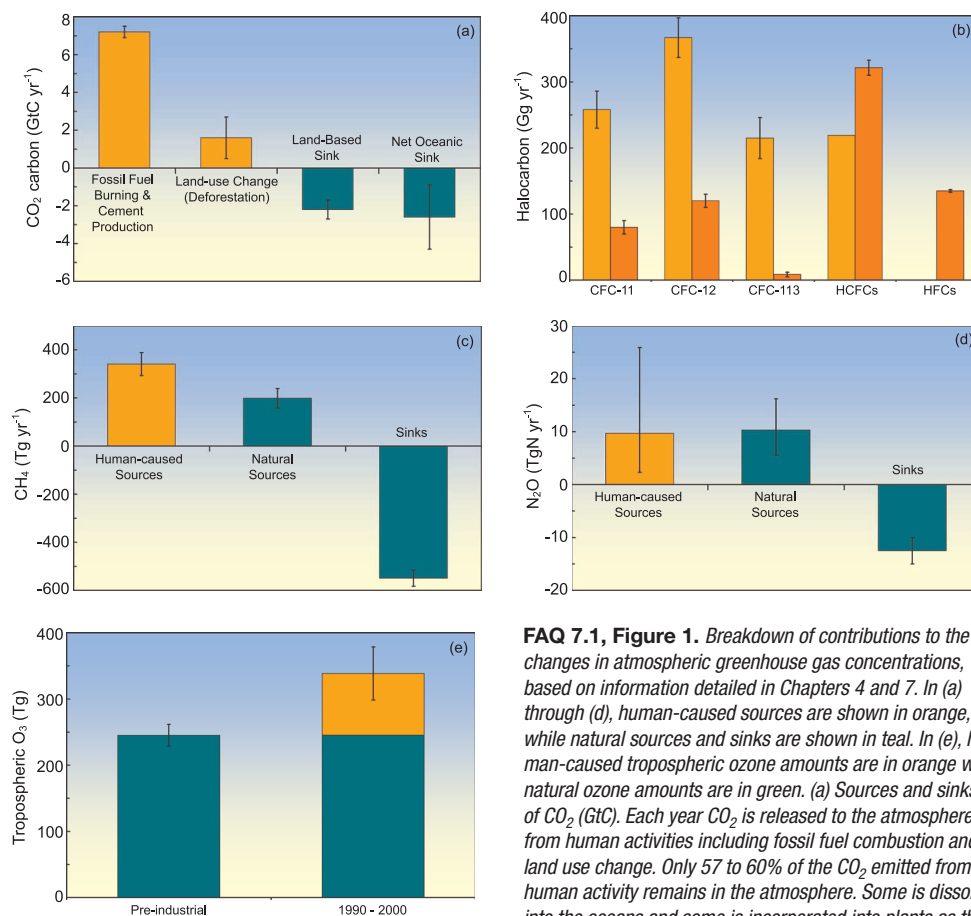
Methane ( $\text{CH}_4$ ) sources to the atmosphere generated by human activities exceed  $\text{CH}_4$  sources from natural systems (Figure 1c). Between 1960 and 1999,  $\text{CH}_4$  concentrations grew an average of at least six times faster than over any 40-year period of the two millennia before 1800, despite a near-zero growth rate since 1980. The main natural source of  $\text{CH}_4$  to the atmosphere is wetlands. Additional natural sources include termites, oceans, vegetation and  $\text{CH}_4$  hydrates. The human activities that produce  $\text{CH}_4$  include energy production from coal and natural gas, waste disposal in landfills, raising ruminant animals (e.g., cattle and sheep), rice agriculture and biomass burning. Once emitted,  $\text{CH}_4$  remains in the atmosphere for approximately 8.4 years before removal, mainly by chemical oxidation in the troposphere. Minor sinks for  $\text{CH}_4$  include uptake by soils and eventual destruction in the stratosphere.

## Nitrous Oxide

Nitrous oxide ( $\text{N}_2\text{O}$ ) sources to the atmosphere from human activities are approximately equal to  $\text{N}_2\text{O}$  sources from natural systems (Figure 1d). Between 1960 and 1999,  $\text{N}_2\text{O}$  concentrations grew an average of at least two times faster than over any 40-year period of the two millennia before 1800. Natural sources of  $\text{N}_2\text{O}$  include oceans, chemical oxidation of ammonia in the atmosphere, and soils. Tropical soils are a particularly important source of  $\text{N}_2\text{O}$  to the atmosphere. Human activities that emit  $\text{N}_2\text{O}$  include transformation of fertilizer nitrogen into  $\text{N}_2\text{O}$  and its subsequent emission from agricultural soils, biomass burning, raising cattle and some industrial activities, including nylon manufacture. Once emitted,  $\text{N}_2\text{O}$  remains in the atmosphere for approximately 114 years before removal, mainly by destruction in the stratosphere.

## Tropospheric Ozone

Tropospheric ozone is produced by photochemical reactions in the atmosphere involving forerunner chemicals such as carbon monoxide,  $\text{CH}_4$ , volatile organic compounds and nitrogen oxides. These chemicals are emitted by natural biological processes and by human activities including land use change and fuel combustion. Because tropospheric ozone is relatively short-lived, lasting for a few days to weeks in the atmosphere, its distributions are highly variable and tied to the abundance of its forerunner compounds, water vapour and sunlight.



**FAQ 7.1, Figure 1.** Breakdown of contributions to the changes in atmospheric greenhouse gas concentrations, based on information detailed in Chapters 4 and 7. In (a) through (d), human-caused sources are shown in orange, while natural sources and sinks are shown in teal. In (e), human-caused tropospheric ozone amounts are in orange while natural ozone amounts are in green. (a) Sources and sinks of  $\text{CO}_2$  (GtC). Each year  $\text{CO}_2$  is released to the atmosphere from human activities including fossil fuel combustion and land use change. Only 57 to 60% of the  $\text{CO}_2$  emitted from human activity remains in the atmosphere. Some is dissolved into the oceans and some is incorporated into plants as they grow. Land-related fluxes are for the 1990s; fossil fuel and cement fluxes and net ocean uptake are for the period 2000 to 2005. All values and uncertainty ranges are from Table 7.1. (b) Global emissions of CFCs and other halogen-containing compounds for 1990 (light orange) and 2002 (dark orange). These chemicals are exclusively human-produced. Here, 'HCFCs' comprise HCFC-22, -141b and -142b, while 'HFCs' comprise HFC-23, -125, -134a and -152a. One Gg =  $10^9$  g (1,000 tonnes). Most data are from reports listed in Chapter 2. (c) Sources and sinks of  $\text{CH}_4$  of the corresponding aggregate values from Table 7.6. (d) Sources and sinks of  $\text{N}_2\text{O}$ . Human-caused sources of  $\text{N}_2\text{O}$  include the transformation of fertilizer nitrogen into  $\text{N}_2\text{O}$  and its subsequent emission from agricultural soils, biomass burning, cattle and some industrial activities including nylon manufacture. Source values and uncertainties are the midpoints and range limits from Table 7.7.  $\text{N}_2\text{O}$  losses are from Chapter 7.4. (e) Tropospheric ozone in the 19th and early 20th centuries and the 1990 to 2000 period. The increase in tropospheric ozone formation is human-induced, resulting from atmospheric chemical reactions of pollutants emitted by burning of fossil fuels or biofuels. The pre-industrial value and uncertainty range are from Table 4.9 of the IPCC Third Assessment Report (TAR), estimated from reconstructed observations. The present-day total and its uncertainty range are the average and standard deviation of model results quoted in Table 7.9 of this report, excluding those from the TAR.

Tropospheric ozone concentrations are significantly higher in urban air, downwind of urban areas and in regions of biomass burning. The increase of 38% (20–50%) in tropospheric ozone since the pre-industrial era (Figure 1e) is human-caused.

It is very likely that the increase in the combined radiative forcing from  $\text{CO}_2$ ,  $\text{CH}_4$  and  $\text{N}_2\text{O}$  was at least six times faster between 1960 and 1999 than over any 40-year period during the two millennia prior to the year 1800.

## Frequently Asked Question 8.1

# How Reliable Are the Models Used to Make Projections of Future Climate Change?

*There is considerable confidence that climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above. This confidence comes from the foundation of the models in accepted physical principles and from their ability to reproduce observed features of current climate and past climate changes. Confidence in model estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation). Over several decades of development, models have consistently provided a robust and unambiguous picture of significant climate warming in response to increasing greenhouse gases.*

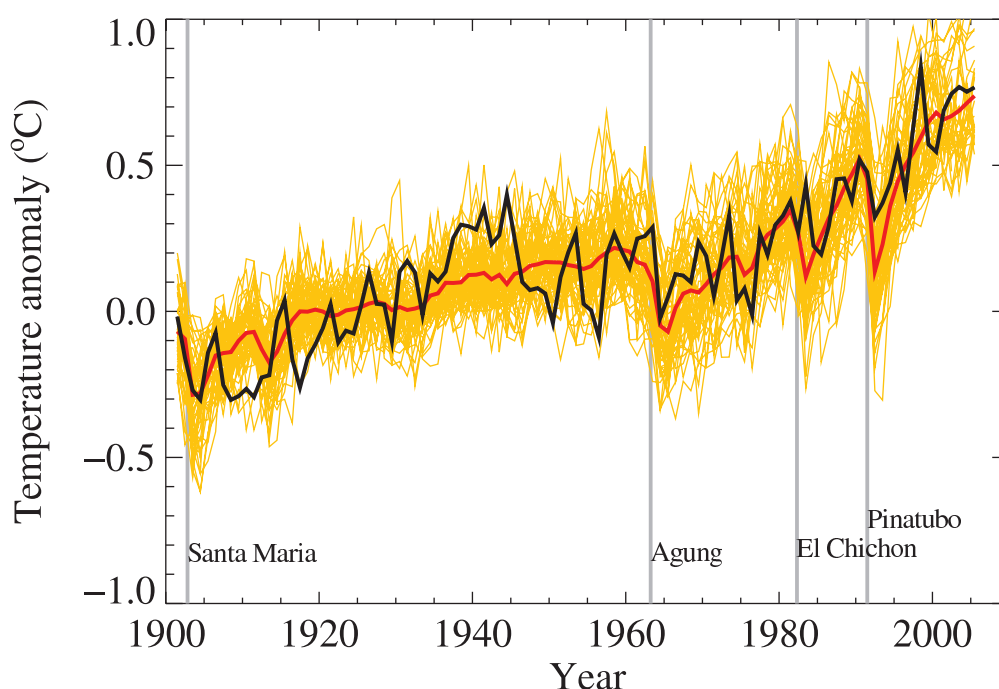
Climate models are mathematical representations of the climate system, expressed as computer codes and run on powerful computers. One source of confidence in models comes from the fact that model fundamentals are based on established physical laws, such as conservation of mass, energy and momentum, along with a wealth of observations.

A second source of confidence comes from the ability of models to simulate important aspects of the current climate. Models are routinely and extensively assessed by comparing their simulations with observations of the atmosphere, ocean, cryosphere and land surface. Unprecedented levels of evaluation have taken place over the last decade in the form of organised multi-model ‘intercomparisons’. Models show significant and

increasing skill in representing many important mean climate features, such as the large-scale distributions of atmospheric temperature, precipitation, radiation and wind, and of oceanic temperatures, currents and sea ice cover. Models can also simulate essential aspects of many of the patterns of climate variability observed across a range of time scales. Examples include the advance and retreat of the major monsoon systems, the seasonal shifts of temperatures, storm tracks and rain belts, and the hemispheric-scale seesawing of extratropical surface pressures (the Northern and Southern ‘annular modes’). Some climate models, or closely related variants, have also been tested by using them to predict weather and make seasonal forecasts. These models demonstrate skill in such forecasts, showing they can represent important features of the general circulation across shorter time scales, as well as aspects of seasonal and interannual variability. Models’ ability to represent these and other important climate features increases our confidence that they represent the essential physical processes important for the simulation of future climate change. (Note that the limitations in climate models’ ability to forecast weather beyond a few days do not limit their ability to predict long-term climate changes, as these are very different types of prediction – see FAQ 1.2.)

(continued)

**FAQ 8.1, Figure 1.** Global mean near-surface temperatures over the 20th century from observations (black) and as obtained from 58 simulations produced by 14 different climate models driven by both natural and human-caused factors that influence climate (yellow). The mean of all these runs is also shown (thick red line). Temperature anomalies are shown relative to the 1901 to 1950 mean. Vertical grey lines indicate the timing of major volcanic eruptions. (Figure adapted from Chapter 9, Figure 9.5. Refer to corresponding caption for further details.)



A third source of confidence comes from the ability of models to reproduce features of past climates and climate changes. Models have been used to simulate ancient climates, such as the warm mid-Holocene of 6,000 years ago or the last glacial maximum of 21,000 years ago (see Chapter 6). They can reproduce many features (allowing for uncertainties in reconstructing past climates) such as the magnitude and broad-scale pattern of oceanic cooling during the last ice age. Models can also simulate many observed aspects of climate change over the instrumental record. One example is that the global temperature trend over the past century (shown in Figure 1) can be modelled with high skill when both human and natural factors that influence climate are included. Models also reproduce other observed changes, such as the faster increase in nighttime than in daytime temperatures, the larger degree of warming in the Arctic and the small, short-term global cooling (and subsequent recovery) which has followed major volcanic eruptions, such as that of Mt. Pinatubo in 1991 (see FAQ 8.1, Figure 1). Model global temperature projections made over the last two decades have also been in overall agreement with subsequent observations over that period (Chapter 1).

Nevertheless, models still show significant errors. Although these are generally greater at smaller scales, important large-scale problems also remain. For example, deficiencies remain in the simulation of tropical precipitation, the El Niño-Southern Oscillation and the Madden-Julian Oscillation (an observed variation in tropical winds and rainfall with a time scale of 30 to 90 days). The ultimate source of most such errors is that many important small-scale processes cannot be represented explicitly in models, and so must be included in approximate form as they interact with larger-scale features. This is partly due to limitations in computing power, but also results from limitations in scientific understanding or in the availability of detailed observations of some physical processes. Significant uncertainties, in particular, are associated with the representation of clouds, and in the resulting cloud responses to climate change. Consequently, models continue to display a substantial range of global temperature change in response to specified greenhouse gas forcing (see Chapter 10). Despite such uncertainties, however, models are unanimous in their predic-

tion of substantial climate warming under greenhouse gas increases, and this warming is of a magnitude consistent with independent estimates derived from other sources, such as from observed climate changes and past climate reconstructions.

Since confidence in the changes projected by global models decreases at smaller scales, other techniques, such as the use of regional climate models, or downscaling methods, have been specifically developed for the study of regional- and local-scale climate change (see FAQ 11.1). However, as global models continue to develop, and their resolution continues to improve, they are becoming increasingly useful for investigating important smaller-scale features, such as changes in extreme weather events, and further improvements in regional-scale representation are expected with increased computing power. Models are also becoming more comprehensive in their treatment of the climate system, thus explicitly representing more physical and biophysical processes and interactions considered potentially important for climate change, particularly at longer time scales. Examples are the recent inclusion of plant responses, ocean biological and chemical interactions, and ice sheet dynamics in some global climate models.

In summary, confidence in models comes from their physical basis, and their skill in representing observed climate and past climate changes. Models have proven to be extremely important tools for simulating and understanding climate, and there is considerable confidence that they are able to provide credible quantitative estimates of future climate change, particularly at larger scales. Models continue to have significant limitations, such as in their representation of clouds, which lead to uncertainties in the magnitude and timing, as well as regional details, of predicted climate change. Nevertheless, over several decades of model development, they have consistently provided a robust and unambiguous picture of significant climate warming in response to increasing greenhouse gases.



## Frequently Asked Question 9.1

# Can Individual Extreme Events be Explained by Greenhouse Warming?

*Changes in climate extremes are expected as the climate warms in response to increasing atmospheric greenhouse gases resulting from human activities, such as the use of fossil fuels. However, determining whether a specific, single extreme event is due to a specific cause, such as increasing greenhouse gases, is difficult, if not impossible, for two reasons: 1) extreme events are usually caused by a combination of factors and 2) a wide range of extreme events is a normal occurrence even in an unchanging climate. Nevertheless, analysis of the warming observed over the past century suggests that the likelihood of some extreme events, such as heat waves, has increased due to greenhouse warming, and that the likelihood of others, such as frost or extremely cold nights, has decreased. For example, a recent study estimates that human influences have more than doubled the risk of a very hot European summer like that of 2003.*

People affected by an extreme weather event often ask whether human influences on the climate could be held to some extent responsible. Recent years have seen many extreme events that some commentators have linked to increasing greenhouse gases. These include the prolonged drought in Australia, the extremely hot summer in Europe in 2003 (see Figure 1), the intense North Atlantic hurricane seasons of 2004 and 2005 and the extreme rainfall events in Mumbai, India in July 2005. Could a human influence such as increased concentrations of greenhouse gases in the atmosphere have ‘caused’ any of these events?

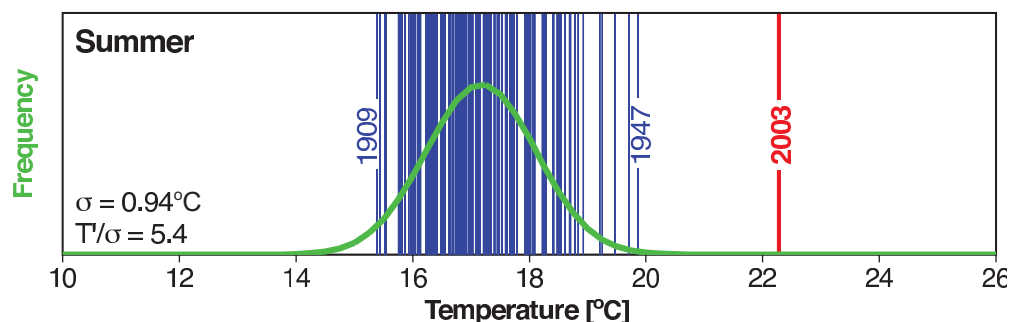
Extreme events usually result from a combination of factors. For example, several factors contributed to the extremely hot European summer of 2003, including a persistent high-pressure system that was associated with very clear skies and dry soil, which left more solar energy available to heat the land because less energy was consumed to evaporate moisture from the soil. Similarly, the formation of a hurricane requires warm sea surface temperatures and specific atmospheric circulation conditions. Because some factors may be strongly affected by human activities, such as sea surface temperatures, but others may not, it is not simple to detect a human influence on a single, specific extreme event.

Nevertheless, it may be possible to use climate models to determine whether human influences have changed the likelihood of certain types of extreme

events. For example, in the case of the 2003 European heat wave, a climate model was run including only historical changes in natural factors that affect the climate, such as volcanic activity and changes in solar output. Next, the model was run again including both human and natural factors, which produced a simulation of the evolution of the European climate that was much closer to that which had actually occurred. Based on these experiments, it was estimated that over the 20th century, human influences more than doubled the risk of having a summer in Europe as hot as that of 2003, and that in the absence of human influences, the risk would probably have been one in many hundred years. More detailed modelling work will be required to estimate the change in risk for specific high-impact events, such as the occurrence of a series of very warm nights in an urban area such as Paris.

The value of such a probability-based approach – ‘Does human influence change the likelihood of an event?’ – is that it can be used to estimate the influence of external factors, such as increases in greenhouse gases, on the frequency of specific types of events, such as heat waves or frost. Nevertheless, careful statistical analyses are required, since the likelihood of individual extremes, such as a late-spring frost, could change due to changes in climate variability as well as changes in average climate conditions. Such analyses rely on climate-model based estimates of climate variability, and thus the climate models used should adequately represent that variability.

The same likelihood-based approach can be used to examine changes in the frequency of heavy rainfall or floods. Climate models predict that human influences will cause an increase in many types of extreme events, including extreme rainfall. There is already evidence that, in recent decades, extreme rainfall has increased in some regions, leading to an increase in flooding.



**FAQ 9.1, Figure 1.** Summer temperatures in Switzerland from 1864 to 2003 are, on average, about 17°C, as shown by the green curve. During the extremely hot summer of 2003, average temperatures exceeded 22°C, as indicated by the red bar (a vertical line is shown for each year in the 137-year record). The fitted Gaussian distribution is indicated in green. The years 1909, 1947 and 2003 are labelled because they represent extreme years in the record. The values in the lower left corner indicate the standard deviation ( $\sigma$ ) and the 2003 anomaly normalised by the 1864 to 2000 standard deviation ( $T'/\sigma$ ). From Schär et al. (2004).

## Frequently Asked Question 9.2

# Can the Warming of the 20th Century be Explained by Natural Variability?

*It is very unlikely that the 20th-century warming can be explained by natural causes. The late 20th century has been unusually warm. Palaeoclimatic reconstructions show that the second half of the 20th century was likely the warmest 50-year period in the Northern Hemisphere in the last 1300 years. This rapid warming is consistent with the scientific understanding of how the climate should respond to a rapid increase in greenhouse gases like that which has occurred over the past century, and the warming is inconsistent with the scientific understanding of how the climate should respond to natural external factors such as variability in solar output and volcanic activity. Climate models provide a suitable tool to study the various influences on the Earth's climate. When the effects of increasing levels of greenhouse gases are included in the models, as well as natural external factors, the models produce good simulations of the warming that has occurred over the past century. The models fail to reproduce the observed warming when run using only natural factors. When human factors are included, the models also simulate a geographic pattern of temperature change around the globe similar to that which has occurred in recent decades. This spatial pattern, which has features such as a greater warming at high northern latitudes, differs from the most important patterns of natural climate variability that are associated with internal climate processes, such as El Niño.*

Variations in the Earth's climate over time are caused by natural internal processes, such as El Niño, as well as changes in external influences. These external influences can be natural in origin, such as volcanic activity and variations in solar output, or caused by human activity, such as greenhouse gas emissions, human-sourced aerosols, ozone depletion and land use change. The role of natural internal processes can be estimated by studying observed variations in climate and by running climate models without changing any of the external factors that affect climate. The effect of external influences can be estimated with models by changing these factors, and by using physical understanding of the processes involved. The combined effects of natural internal variability and natural external factors can also be estimated from climate information recorded in tree rings, ice cores and other types of natural 'thermometers' prior to the industrial age.

The natural external factors that affect climate include volcanic activity and variations in solar output. Explosive volcanic eruptions occasionally eject large amounts of dust and sulphate aerosol high into the atmosphere, temporarily shielding the Earth and reflecting sunlight back to space. Solar output has an 11-year cycle and may also have longer-term variations. Human activities over the last 100 years, particularly the burning of fossil fuels, have caused a rapid increase in carbon dioxide and other greenhouse gases in the atmosphere. Before

the industrial age, these gases had remained at near stable concentrations for thousands of years. Human activities have also caused increased concentrations of fine reflective particles, or 'aerosols', in the atmosphere, particularly during the 1950s and 1960s.

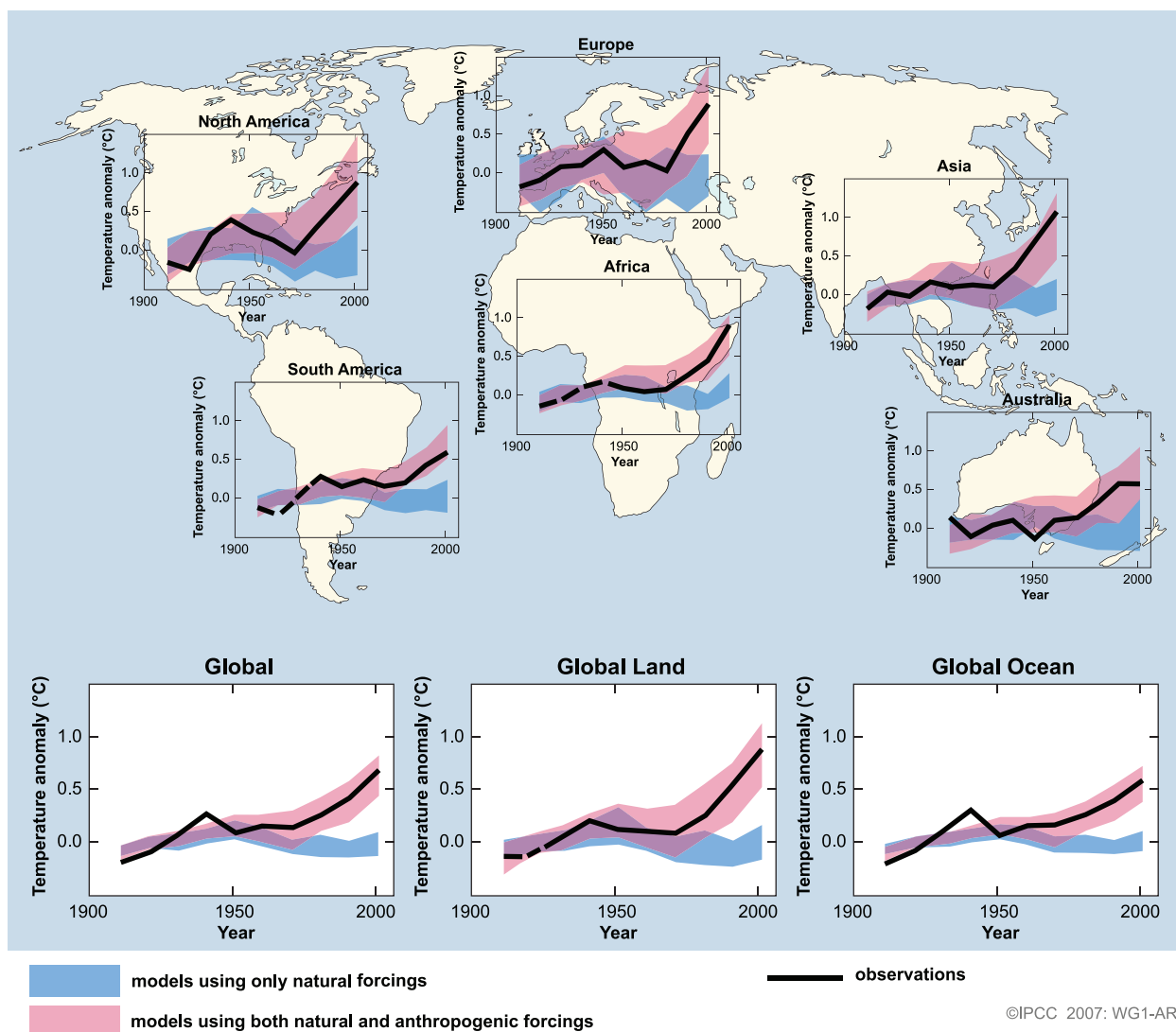
Although natural internal climate processes, such as El Niño, can cause variations in global mean temperature for relatively short periods, analysis indicates that a large portion is due to external factors. Brief periods of global cooling have followed major volcanic eruptions, such as Mt. Pinatubo in 1991. In the early part of the 20th century, global average temperature rose, during which time greenhouse gas concentrations started to rise, solar output was probably increasing and there was little volcanic activity. During the 1950s and 1960s, average global temperatures levelled off, as increases in aerosols from fossil fuels and other sources cooled the planet. The eruption of Mt. Agung in 1963 also put large quantities of reflective dust into the upper atmosphere. The rapid warming observed since the 1970s has occurred in a period when the increase in greenhouse gases has dominated over all other factors.

Numerous experiments have been conducted using climate models to determine the likely causes of the 20th-century climate change. These experiments indicate that models cannot reproduce the rapid warming observed in recent decades when they only take into account variations in solar output and volcanic activity. However, as shown in Figure 1, models are able to simulate the observed 20th-century changes in temperature when they include all of the most important external factors, including human influences from sources such as greenhouse gases and natural external factors. The model-estimated responses to these external factors are detectable in the 20th-century climate globally and in each individual continent except Antarctica, where there are insufficient observations. The human influence on climate very likely dominates over all other causes of change in global average surface temperature during the past half century.

An important source of uncertainty arises from the incomplete knowledge of some external factors, such as human-sourced aerosols. In addition, the climate models themselves are imperfect. Nevertheless, all models simulate a pattern of response to greenhouse gas increases from human activities that is similar to the observed pattern of change. This pattern includes more warming over land than over the oceans. This pattern of change, which differs from the principal patterns of temperature change associated with natural internal variability, such as El Niño, helps to distinguish the response to greenhouse gases from that of natural external factors. Models and observations also both show warming in the lower part of

*(continued)*





**FAQ 9.2, Figure 1.** Temperature changes relative to the corresponding average for 1901-1950 (°C) from decade to decade from 1906 to 2005 over the Earth's continents, as well as the entire globe, global land area and the global ocean (lower graphs). The black line indicates observed temperature change, while the coloured bands show the combined range covered by 90% of recent model simulations. Red indicates simulations that include natural and human factors, while blue indicates simulations that include only natural factors. Dashed black lines indicate decades and continental regions for which there are substantially fewer observations. Detailed descriptions of this figure and the methodology used in its production are given in the Supplementary Material, Appendix 9.C.

the atmosphere (the troposphere) and cooling higher up in the stratosphere. This is another 'fingerprint' of change that reveals the effect of human influence on the climate. If, for example, an increase in solar output had been responsible for the recent climate warming, both the troposphere and the stratosphere would have warmed. In addition, differences in the timing of the human and natural external influences help to distinguish the climate responses to these factors. Such considerations increase confidence that human rather than natural factors were the dominant cause of the global warming observed over the last 50 years.

Estimates of Northern Hemisphere temperatures over the last one to two millennia, based on natural 'thermometers' such as tree rings that vary in width or density as temperatures change, and historical weather records, provide additional evidence that

the 20th-century warming cannot be explained by only natural internal variability and natural external forcing factors. Confidence in these estimates is increased because prior to the industrial era, much of the variation they show in Northern Hemisphere average temperatures can be explained by episodic cooling caused by large volcanic eruptions and by changes in the Sun's output. The remaining variation is generally consistent with the variability simulated by climate models in the absence of natural and human-induced external factors. While there is uncertainty in the estimates of past temperatures, they show that it is likely that the second half of the 20th century was the warmest 50-year period in the last 1300 years. The estimated climate variability caused by natural factors is small compared to the strong 20th-century warming.

## Frequently Asked Question 10.1

# Are Extreme Events, Like Heat Waves, Droughts or Floods, Expected to Change as the Earth's Climate Changes?

*Yes; the type, frequency and intensity of extreme events are expected to change as Earth's climate changes, and these changes could occur even with relatively small mean climate changes. Changes in some types of extreme events have already been observed, for example, increases in the frequency and intensity of heat waves and heavy precipitation events (see FAQ 3.3).*

In a warmer future climate, there will be an increased risk of more intense, more frequent and longer-lasting heat waves. The European heat wave of 2003 is an example of the type of extreme heat event lasting from several days to over a week that is likely to become more common in a warmer future climate. A related aspect of temperature extremes is that there is likely to be a decrease in the daily (diurnal) temperature range in most regions. It is also likely that a warmer future climate would have fewer frost days (i.e., nights where the temperature dips below freezing). Growing season length is related to number of frost days, and has been projected to increase as climate warms. There is likely to be a decline in the frequency of cold air outbreaks (i.e., periods of extreme cold lasting from several days to over a week) in NH winter in most areas. Exceptions could occur in areas with the smallest reductions of extreme cold in western North America, the North Atlantic and southern Europe and Asia due to atmospheric circulation changes.

In a warmer future climate, most Atmosphere-Ocean General Circulation Models project increased summer dryness and winter wetness in most parts of the northern middle and high latitudes. Summer dryness indicates a greater risk of drought. Along with the risk of drying, there is an increased chance of intense precipitation and flooding due to the greater water-holding capacity of a warmer atmosphere. This has already been observed and is projected to continue because in a warmer world, precipitation tends to be concentrated into more intense events, with longer periods of little precipitation in between. Therefore, intense and heavy downpours would be interspersed with longer relatively dry periods. Another aspect of these projected changes is that wet extremes are projected to become more severe in many areas

where mean precipitation is expected to increase, and dry extremes are projected to become more severe in areas where mean precipitation is projected to decrease.

In concert with the results for increased extremes of intense precipitation, even if the wind strength of storms in a future climate did not change, there would be an increase in extreme rainfall intensity. In particular, over NH land, an increase in the likelihood of very wet winters is projected over much of central and northern Europe due to the increase in intense precipitation during storm events, suggesting an increased chance of flooding over Europe and other mid-latitude regions due to more intense rainfall and snowfall events producing more runoff. Similar results apply for summer precipitation, with implications for more flooding in the Asian monsoon region and other tropical areas. The increased risk of floods in a number of major river basins in a future warmer climate has been related to an increase in river discharge with an increased risk of future intense storm-related precipitation events and flooding. Some of these changes would be extensions of trends already underway.

There is evidence from modelling studies that future tropical cyclones could become more severe, with greater wind speeds and more intense precipitation. Studies suggest that such changes may already be underway; there are indications that the average number of Category 4 and 5 hurricanes per year has increased over the past 30 years. Some modelling studies have projected a decrease in the number of tropical cyclones globally due to the increased stability of the tropical troposphere in a warmer climate, characterised by fewer weak storms and greater numbers of intense storms. A number of modelling studies have also projected a general tendency for more intense but fewer storms outside the tropics, with a tendency towards more extreme wind events and higher ocean waves in several regions in association with those deepened cyclones. Models also project a poleward shift of storm tracks in both hemispheres by several degrees of latitude.

## Frequently Asked Question 10.2

# How Likely are Major or Abrupt Climate Changes, such as Loss of Ice Sheets or Changes in Global Ocean Circulation?

*Abrupt climate changes, such as the collapse of the West Antarctic Ice Sheet, the rapid loss of the Greenland Ice Sheet or large-scale changes of ocean circulation systems, are not considered likely to occur in the 21st century, based on currently available model results. However, the occurrence of such changes becomes increasingly more likely as the perturbation of the climate system progresses.*

Physical, chemical and biological analyses from Greenland ice cores, marine sediments from the North Atlantic and elsewhere and many other archives of past climate have demonstrated that local temperatures, wind regimes and water cycles can change rapidly within just a few years. The comparison of results from records in different locations of the world shows that in the past major changes of hemispheric to global extent occurred. This has led to the notion of an unstable past climate that underwent phases of abrupt change. Therefore, an important concern is that the continued growth of greenhouse gas concentrations in the atmosphere may constitute a perturbation sufficiently strong to trigger abrupt changes in the climate system. Such interference with the climate system could be considered dangerous, because it would have major global consequences.

Before discussing a few examples of such changes, it is useful to define the terms ‘abrupt’ and ‘major’. ‘Abrupt’ conveys the meaning that the changes occur much faster than the perturbation inducing the change; in other words, the response is nonlinear. A ‘major’ climate change is one that involves changes that exceed the range of current natural variability and have a spatial extent ranging from several thousand kilometres to global. At local to regional scales, abrupt changes are a common characteristic of natural climate variability. Here, isolated, short-lived events that are more appropriately referred to as ‘extreme events’ are not considered, but rather large-scale changes that evolve rapidly and persist for several years to decades. For instance, the mid-1970s shift in sea surface temperatures in the Eastern Pacific, or the salinity reduction in the upper 1,000 m of the Labrador Sea since the mid-1980s, are examples of abrupt events with local to regional consequences, as opposed to the larger-scale, longer-term events that are the focus here.

One example is the potential collapse, or shut-down of the Gulf Stream, which has received broad public attention. The Gulf Stream is a primarily horizontal current in the north-western Atlantic Ocean driven by winds. Although a stable feature of the general circulation of the ocean, its northern extension, which feeds deep-water formation in the Greenland-Norwegian-Iceland Seas and thereby delivers substantial amounts of heat to these seas and nearby land areas, is influenced strongly by changes in the density of the surface waters in these areas. This current

constitutes the northern end of a basin-scale meridional overturning circulation (MOC) that is established along the western boundary of the Atlantic basin. A consistent result from climate model simulations is that if the density of the surface waters in the North Atlantic decreases due to warming or a reduction in salinity, the strength of the MOC is decreased, and with it, the delivery of heat into these areas. Strong sustained reductions in salinity could induce even more substantial reduction, or complete shut-down of the MOC in all climate model projections. Such changes have indeed happened in the distant past.

The issue now is whether the increasing human influence on the atmosphere constitutes a strong enough perturbation to the MOC that such a change might be induced. The increase in greenhouse gases in the atmosphere leads to warming and an intensification of the hydrological cycle, with the latter making the surface waters in the North Atlantic less salty as increased rain leads to more freshwater runoff to the ocean from the region’s rivers. Warming also causes land ice to melt, adding more freshwater and further reducing the salinity of ocean surface waters. Both effects would reduce the density of the surface waters (which must be dense and heavy enough to sink in order to drive the MOC), leading to a reduction in the MOC in the 21st century. This reduction is predicted to proceed in lockstep with the warming: none of the current models simulates an abrupt (nonlinear) reduction or a complete shut-down in this century. There is still a large spread among the models’ simulated reduction in the MOC, ranging from virtually no response to a reduction of over 50% by the end of the 21st century. This cross-model variation is due to differences in the strengths of atmosphere and ocean feedbacks simulated in these models.

Uncertainty also exists about the long-term fate of the MOC. Many models show a recovery of the MOC once climate is stabilised. But some models have thresholds for the MOC, and they are passed when the forcing is strong enough and lasts long enough. Such simulations then show a gradual reduction of the MOC that continues even after climate is stabilised. A quantification of the likelihood of this occurring is not possible at this stage. Nevertheless, even if this were to occur, Europe would still experience warming, since the radiative forcing caused by increasing greenhouse gases would overwhelm the cooling associated with the MOC reduction. Catastrophic scenarios suggesting the beginning of an ice age triggered by a shutdown of the MOC are thus mere speculations, and no climate model has produced such an outcome. In fact, the processes leading to an ice age are sufficiently well understood and so completely different from those discussed here, that we can confidently exclude this scenario.

*(continued)*

Irrespective of the long-term evolution of the MOC, model simulations agree that the warming and resulting decline in salinity will significantly reduce deep and intermediate water formation in the Labrador Sea during the next few decades. This will alter the characteristics of the intermediate water masses in the North Atlantic and eventually affect the deep ocean. The long-term effects of such a change are unknown.

Other widely discussed examples of abrupt climate changes are the rapid disintegration of the Greenland Ice Sheet, or the sudden collapse of the West Antarctic Ice Sheet. Model simulations and observations indicate that warming in the high latitudes of the Northern Hemisphere is accelerating the melting of the Greenland Ice Sheet, and that increased snowfall due to the intensified hydrological cycle is unable to compensate for this melting. As a consequence, the Greenland Ice Sheet may shrink substantially in the coming centuries. Moreover, results suggest that there is a critical temperature threshold beyond which the Greenland Ice Sheet would be committed to disappearing completely, and that threshold could be crossed in this century. However, the total melting of the Greenland Ice Sheet, which

would raise global sea level by about seven metres, is a slow process that would take many hundreds of years to complete.

Recent satellite and *in situ* observations of ice streams behind disintegrating ice shelves highlight some rapid reactions of ice sheet systems. This raises new concern about the overall stability of the West Antarctic Ice Sheet, the collapse of which would trigger another five to six metres of sea level rise. While these streams appear buttressed by the shelves in front of them, it is currently unknown whether a reduction or failure of this buttressing of relatively limited areas of the ice sheet could actually trigger a widespread discharge of many ice streams and hence a destabilisation of the entire West Antarctic Ice Sheet. Ice sheet models are only beginning to capture such small-scale dynamical processes that involve complicated interactions with the glacier bed and the ocean at the perimeter of the ice sheet. Therefore, no quantitative information is available from the current generation of ice sheet models as to the likelihood or timing of such an event.

### Frequently Asked Question 10.3

## If Emissions of Greenhouse Gases are Reduced, How Quickly do Their Concentrations in the Atmosphere Decrease?

*The adjustment of greenhouse gas concentrations in the atmosphere to reductions in emissions depends on the chemical and physical processes that remove each gas from the atmosphere. Concentrations of some greenhouse gases decrease almost immediately in response to emission reduction, while others can actually continue to increase for centuries even with reduced emissions.*

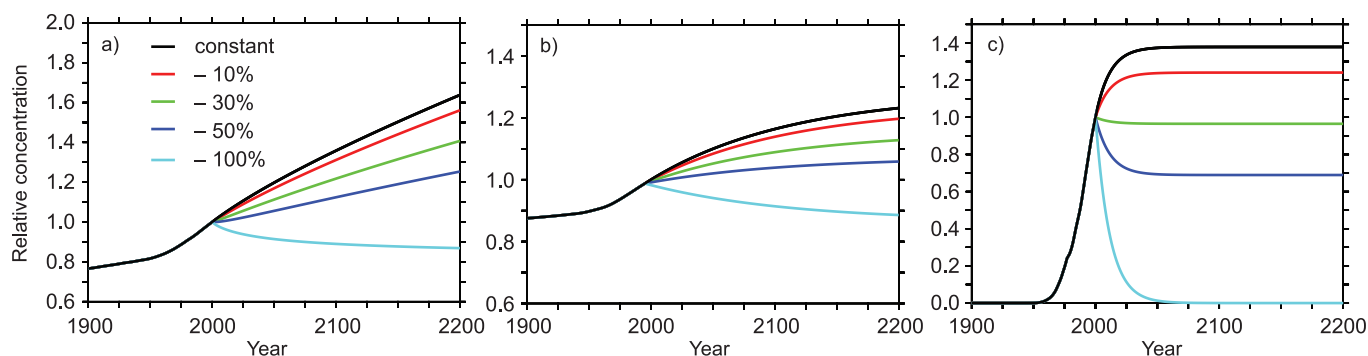
The concentration of a greenhouse gas in the atmosphere depends on the competition between the rates of emission of the gas into the atmosphere and the rates of processes that remove it from the atmosphere. For example, carbon dioxide ( $\text{CO}_2$ ) is exchanged between the atmosphere, the ocean and the land through processes such as atmosphere-ocean gas transfer and chemical (e.g., weathering) and biological (e.g., photosynthesis) processes. While more than half of the  $\text{CO}_2$  emitted is currently removed from the atmosphere within a century, some fraction (about 20%) of emitted  $\text{CO}_2$  remains in the atmosphere for many millennia. Because of slow removal processes, atmospheric  $\text{CO}_2$  will continue to increase in the long term even if its emission is substantially reduced from present levels. Methane ( $\text{CH}_4$ ) is removed by chemical processes in the atmosphere, while nitrous oxide ( $\text{N}_2\text{O}$ ) and some halocarbons are destroyed in the upper atmosphere by solar radiation. These processes each operate at different time scales ranging from years to millennia. A measure for this is the lifetime of a gas in the atmosphere, defined as the time it takes for a perturbation to be reduced to 37% of its initial amount. While for  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , and other trace gases such as hydrochlorofluorocarbon-22 (HCFC-22), a refrigerant fluid, such lifetimes can be reasonably determined (for  $\text{CH}_4$  it is about 12 yr, for  $\text{N}_2\text{O}$  about 110 yr and for HCFC-22 about 12 yr), a lifetime for  $\text{CO}_2$  cannot be defined.

The change in concentration of any trace gas depends in part on how its emissions evolve over time. If emissions increase with time, the atmospheric concentration will also increase with time, regardless of the atmospheric lifetime of the gas. However, if actions are taken to reduce the emissions, the fate of the trace gas concentration will depend on the relative changes not only of emissions but also of its removal processes. Here we show how the lifetimes and removal processes of different gases dictate the evolution of concentrations when emissions are reduced.

As examples, FAQ 10.3, Figure 1 shows test cases illustrating how the future concentration of three trace gases would respond to illustrative changes in emissions (represented here as a response to an imposed pulse change in emission). We consider  $\text{CO}_2$ , which has no specific lifetime, as well as a trace gas with a well-defined long lifetime on the order of a century (e.g.,  $\text{N}_2\text{O}$ ), and a trace gas with a well-defined short lifetime on the order of decade (such as  $\text{CH}_4$ , HCFC-22 or other halocarbons). For each gas, five illustrative cases of future emissions are presented: stabilisation of emissions at present-day levels, and immediate emission reduction by 10%, 30%, 50% and 100%.

The behaviour of  $\text{CO}_2$  (Figure 1a) is completely different from the trace gases with well-defined lifetimes. Stabilisation of  $\text{CO}_2$  emissions at current levels would result in a continuous increase of atmospheric  $\text{CO}_2$  over the 21st century and beyond, whereas for a gas with a lifetime on the order of a century (Figure 1b) or a decade (Figure 1c), stabilisation of emissions at current levels would lead to a stabilisation of its concentration at a level higher than today within a couple of centuries, or decades, respectively. In fact, only in the case of essentially complete elimination of

(continued)



**FAQ 10.3, Figure 1.** (a) Simulated changes in atmospheric  $\text{CO}_2$  concentration relative to the present-day for emissions stabilised at the current level (black), or at 10% (red), 30% (green), 50% (dark blue) and 100% (light blue) lower than the current level; (b) as in (a) for a trace gas with a lifetime of 120 years, driven by natural and anthropogenic fluxes; and (c) as in (a) for a trace gas with a lifetime of 12 years, driven by only anthropogenic fluxes.

emissions can the atmospheric concentration of CO<sub>2</sub> ultimately be stabilised at a constant level. All other cases of moderate CO<sub>2</sub> emission reductions show increasing concentrations because of the characteristic exchange processes associated with the cycling of carbon in the climate system.

More specifically, the rate of emission of CO<sub>2</sub> currently greatly exceeds its rate of removal, and the slow and incomplete removal implies that small to moderate reductions in its emissions would not result in stabilisation of CO<sub>2</sub> concentrations, but rather would only reduce the rate of its growth in coming decades. A 10% reduction in CO<sub>2</sub> emissions would be expected to reduce the growth rate by 10%, while a 30% reduction in emissions would similarly reduce the growth rate of atmospheric CO<sub>2</sub> concentrations by 30%. A 50% reduction would stabilise atmospheric CO<sub>2</sub>, but only for less than a decade. After that, atmospheric CO<sub>2</sub> would be expected to rise again as the land and ocean sinks decline owing to well-known chemical and biological adjustments. Complete elimination of CO<sub>2</sub> emissions is estimated to lead to a slow decrease in atmospheric CO<sub>2</sub> of about 40 ppm over the 21st century.

The situation is completely different for the trace gases with a well-defined lifetime. For the illustrative trace gas with a lifetime of the order of a century (e.g., N<sub>2</sub>O), emission reduction of more than 50% is required to stabilise the concentrations close to present-day values (Figure 1b). Constant emission leads to a stabilisation of the concentration within a few centuries.

In the case of the illustrative gas with the short lifetime, the present-day loss is around 70% of the emissions. A reduction in emissions of less than 30% would still produce a short-term increase in concentration in this case, but, in contrast to CO<sub>2</sub>, would lead to stabilisation of its concentration within a couple of decades (Figure 1c). The decrease in the level at which the concentration of such a gas would stabilise is directly proportional to the emission reduction. Thus, in this illustrative example, a reduction in emissions of this trace gas larger than 30% would be required to stabilise concentrations at levels significantly below those at present. A complete cut-off of the emissions would lead to a return to pre-industrial concentrations within less than a century for a trace gas with a lifetime of the order of a decade.



## Frequently Asked Question 11.1

# Do Projected Changes in Climate Vary from Region to Region?

*Climate varies from region to region. This variation is driven by the uneven distribution of solar heating, the individual responses of the atmosphere, oceans and land surface, the interactions between these, and the physical characteristics of the regions. The perturbations of the atmospheric constituents that lead to global changes affect certain aspects of these complex interactions. Some human-induced factors that affect climate ('forcings') are global in nature, while others differ from one region to another. For example, carbon dioxide, which causes warming, is distributed evenly around the globe, regardless of where the emissions originate, whereas sulphate aerosols (small particles) that offset some of the warming tend to be regional in their distribution. Furthermore, the response to forcings is partly governed by feedback processes that may operate in different regions from those in which the forcing is greatest. Thus, the projected changes in climate will also vary from region to region.*

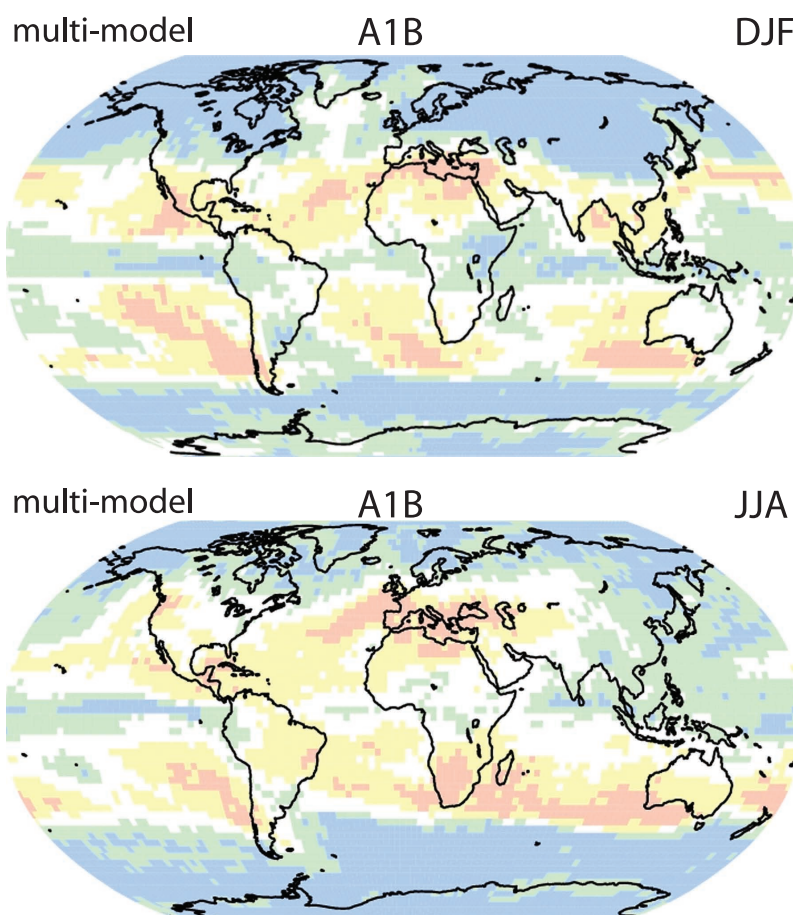
Latitude is a good starting point for considering how changes in climate will affect a region. For example, while warming is expected everywhere on Earth, the amount of projected warming generally increases from the tropics to the poles in the Northern Hemisphere. Precipitation is more complex, but also has some latitude-dependent features. At latitudes adjacent to the polar regions, precipitation is projected to increase, while decreases are projected in many regions adjacent to the tropics (see Figure 1). Increases in tropical precipitation are projected during rainy seasons (e.g., monsoons), and over the tropical Pacific in particular.

Location with respect to oceans and mountain ranges is also an important factor. Generally, the interiors of continents are projected to warm more than the coastal areas. Precipitation responses are especially sensitive not only to the continental geometry, but to the shape of nearby mountain ranges and wind flow direction. Monsoons, extratropical cyclones and hurricanes/typhoons are all influenced in different ways by these region-specific features.

Some of the most difficult aspects of understanding and projecting changes in regional climate relate to possible changes in the circulation of the atmosphere and oceans, and their patterns of variability. Although general statements covering a variety of regions with

qualitatively similar climates can be made in some cases, nearly every region is idiosyncratic in some ways. This is true whether it is the coastal zones surrounding the subtropical Mediterranean Sea, the extreme weather in the North American interior that depends on moisture transport from the Gulf of Mexico, or the interactions between vegetation distribution, oceanic temperatures and atmospheric circulation that help control the southern limit of the Sahara Desert.

While developing an understanding of the correct balance of global and regional factors remains a challenge, the understanding of these factors is steadily growing, increasing our confidence in regional projections.



**FAQ 11.1, Figure 1.** Blue and green areas on the map are by the end of the century projected to experience increases in precipitation, while areas in yellow and pink are projected to have decreases. The top panel shows projections for the period covering December, January and February, while the bottom panel shows projections for the period covering June, July and August.