Earth System Processes

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We experience weather every day in all its incredible variety. Most of the time it is familiar, yet it never repeats exactly. We also experience the changing seasons and associated kinds of weather. In summer, fine sunny days may be interrupted by outbreaks of rain and thunderstorms. Outside of the tropics as winter approaches, the days get shorter, it gets colder and the weather typically fluctuates from warmer and fine spells to cooler and rainy or maybe snowy conditions. In the tropics, the seasonal variations are more often experienced as monsoonal fluctuations between a wet season and a somewhat longer dry season. These seasonal changes are the largest climate changes we experience at any given location. Because they arise in a well understood way from the regular orbit of the Earth around the Sun, we expect them, and we look forward to them. We plan summer vacations and winter ski trips accordingly. Farmers plan their crops and harvests around the seasonal cycle. By comparison, variations in the average weather from one year to the next are quite modest, and longer-term changes in climate occurring over decades or human lifetimes may be even smaller. Nevertheless, these variations can be very disruptive and costly if we do not expect them.

Climate changes, lasting decades to millennia, have occurred in the past as a result of various natural influences. Interannual variations are also an important ingredient of climate and can arise through, for example, interactions between the atmosphere and the oceans, as is the case with El Niño.

This article discusses weather and climate variations in the context of the Earth system as a whole, and provides a basis for understanding the reasons why climate may vary, and how these variations may be manifested in terms of weather. The main focus of this article is on the atmosphere, which is the most variable component of the Earth system; it is also where we live and it provides the air we breathe. But the atmosphere interacts with the oceans, the land surface and its vegetation, and with the other components of the climate system, so those too are important, even from this perspective. Their role in climate is also addressed in this article.

*Like the oceans, the atmosphere is a global commons (Soroos, 1997) (*see ***Commons, Tragedy of the****, Volume 5). It is globally connected and air that is over one nation can easily lie over another on the next continent a day later. Recent attempts by manned balloons to circumnavigate the globe have dramatically shown how the winds can carry a balloon half way around the world in a week or less and that air currents can often take the balloon in unwanted directions. So the atmosphere belongs to no one nation; rather all nations may use it for their own purposes (such as discharging pollution into it) and thus it is also subject to abuse and the phenomenon known as the "tragedy of the commons" (Hardin, 1968) in which the best interests of an individual or individual nation may conflict with the health of the commons itself. Human influences on climate change, often referred to as "global warming," are therefore also discussed.*

The Earth System includes many other important processes and phenomena that are covered elsewhere in this Encyclopedia. Even in the atmosphere alone, environmental problems include ozone depletion and the "ozone hole," acid rain, air quality and pollution, and, a few decades ago, radioactivity and atomic bomb test debris. Other problems exist in the oceans and on land, such as biodiversity, deforestation, desertification, exploitation of water resources and fisheries, and so on. Many of these environmental problems can be exacerbated by climate change, so that it is the intersection of these problems and climate change that will make for major challenges in the years ahead.

THE EARTH AND CLIMATE SYSTEM

Our planet orbits the Sun once per year at an average distance of 1.50×10^{11} m. Looking directly at the Sun, the Earth receives an average radiation of $1368\,\mathrm{W\,m^{-2}}$ at this distance. This value is referred to as the total solar irradiance; this value used to be called the "solar constant" even though it does vary by small amounts with the sunspot cycle and related changes on the Sun (*see* **Solar Irradiance and Climate**, Volume 1). The Earth's shape is close to that of an oblate spheroid, with an average radius of 6371 km, but it varies from 6378 km at the equator to 6357 km at the poles. The Earth's daily rotation is about an axis with a current tilt, relative to the ecliptic plane, of 23.5°. The Earth's annual orbit around the Sun is slightly elliptical, presently bringing the Earth closest to the Sun on January 3rd (called *perihelion*). The rotation gives rise to the seasons because the Northern Hemisphere (NH) points more toward the Sun in June while it is the Southern Hemisphere's (SH) turn in late December.

The Earth also turns on its axis once per day with an angular velocity of $7.292 \times 10^{-5}\ s^{-1}$. This rotation gives us the day–night cycle. A consequence of the Earth's roughly spherical shape and the rotation is that the average solar radiation received at the top of the Earth's atmosphere is the solar constant divided by 4, which is the ratio of the Earth's surface area ($4\pi a^2$, where a is the mean radius) to that of the cross-section (πa^2). On timescales of tens of thousands of years, the Earth's orbit slowly changes, the shape of the orbit is altered, the tilt changes, and the Earth precesses on its axis like a rotating top, all of which combine to alter the latitudinal and seasonal distribution of solar radiation received by the Earth (*see* **Orbital Variations**, Volume 1). These variations have been associated with the Earth's glacial cycling (*see* **Milankovitch, Milutin**, Volume 1).

The rotation of the Earth provides a centrifugal force outward, away from the axis of rotation. This force is greatest on the equator at the Earth's surface. Meanwhile, the equatorial bulge in the Earth's shape, which presumably arises from the rotation, provides a greater gravitational attraction than at high latitudes. Thus, it is not a coincidence that the effective net gravity at the surface, which is a combination of the actual gravitational attraction and the centrifugal force, is almost constant and at right angles to the surface, thereby allowing the Earth to be treated as a sphere for many purposes.

The Earth System can be altered by effects or influences from outside the planet, usually regarded as externally imposed. Most important are the Sun and its output, the Earth's rotation rate, Sun–Earth geometry and the slowly changing orbit, the physical make up of the Earth system such as the distribution of land and ocean, the geographic features on the land, the ocean bottom topography and basin configurations, and the mass and basic composition of the atmosphere and ocean. These components determine the mean climate, which can be affected by variations due to these natural causes. For example, a change in the average net radiation at the top of the atmosphere due to perturbations in the incident solar radiation or the emergent infrared radiation leads to a change in heating. Changes in the net incident radiation energy at the Earth's surface can occur from the changes internal to the Sun or, for example, from changes in atmospheric composition such as may arise from natural events like volcanoes, which can create a cloud of debris that blocks a portion of the incoming solar radiation. Other forcings that might be regarded as external include those arising as a result of human activities.

The internal interactive components in the climate system (Figure 1) include the atmosphere, the oceans, sea ice, the land, snow cover, land ice, and fresh water reservoirs. The greatest variations in the composition of the atmosphere involve water in various phases, which include water vapor, clouds of liquid water, ice crystal clouds, and rain, snow, and hail (*see* **Hydrologic Cycle**, Volume 1). However, other constituents of the atmosphere and the oceans can also change, thereby bringing considerations of atmospheric chemistry, marine biogeochemistry, and land surface exchanges into climate change.

The atmosphere is the most volatile part of the climate system; for example, winds in jet streams at about 10 km (32800 feet) altitude often exceed $50\ m\ s^{-1}$ (112 miles per hour) and sometimes even double these values. Changes in weather can occur in just a few hours. The atmosphere is quite a thin envelope around the planet, with 90% of its mass of 5.1×10^{18} kg within about 16 km (roughly 10 miles) of the surface (about one four hundredth the radius of the Earth). This relative shallowness of the Earth's atmosphere often allows the atmospheric motions to be considered as occurring at the Earth's surface. For example, satellite photographs of Earth appear to show clouds hugging the surface.

The atmosphere is composed of several fairly distinct layers. Immediately above the surface is the troposphere, which extends upwards to about 10 km in the extratropics and 16 km in the tropics. About 80–90% of the atmosphere is contained in the troposphere. It is defined as the layer where the temperature generally decreases with altitude and is the region where most of what we call "weather" occurs. The troposphere is the region where vertical air movements occur and produce clouds and precipitation in rising air and clear skies in gently subsiding air.

The second layer is the stratosphere, which extends to about 50 km in altitude. Because this is a region where temperatures generally increase with height, it is very stable, resists vertical motions, and is highly stratified (as the name implies). Many jet aircraft fly in the lower stratosphere in the relatively non-turbulent conditions above tropospheric weather systems. In this region, oxygen molecules, consisting of two oxygen atoms, are broken apart by intense solar radiation in the ultraviolet and participate in a process to form ozone molecules, in which three atoms of oxygen are combined. So the main ozone layer is contained in the stratosphere (*see* **Stratosphere, Chemistry**, Volume 1). Its presence shields the surface from harmful ultraviolet rays, making it possible for life to exist (*see* **Ultraviolet Radiation**, Volume 1).

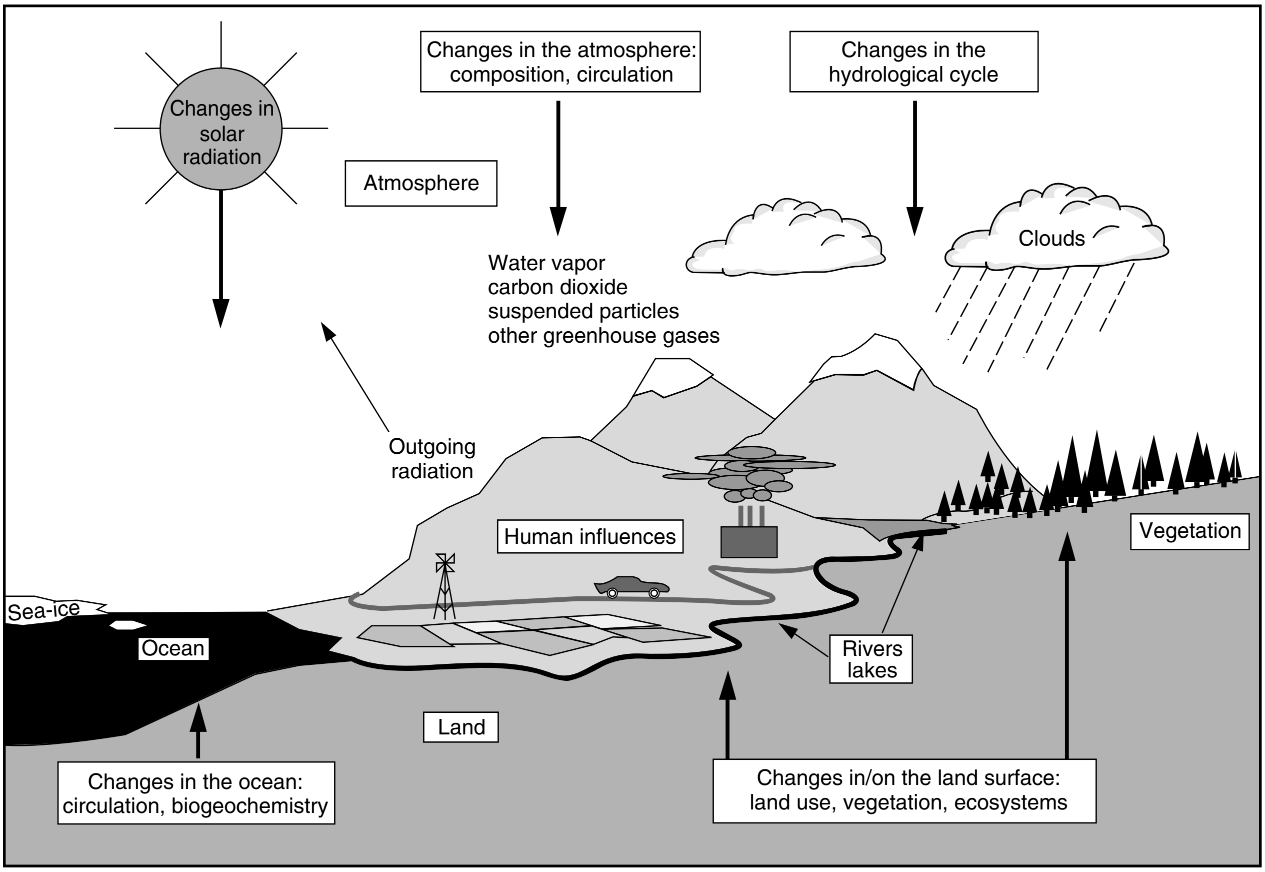

Figure 1 Schematic view of the components of the global climate system (bold), their processes and interactions (thin arrows) and some aspects that may change (bold arrows). (Adapted from Trenberth *et al.*, 1996)

Moving upward, the third atmospheric layer is the mesosphere, which extends to roughly 80 km with temperatures decreasing with altitude. Above the mesosphere is the thermosphere, in which the temperature again increases with height. The thermosphere contains only 0.01% of the atmosphere and it is in this region that atmospheric gases are ionized by energetic and short ultraviolet solar radiation, so that it includes most of the ionosphere. The ionosphere is particularly important because it influences radiowave transmission.

The other main fluid component of the climate system is the oceans. The oceans contain slightly more than 97% of the roughly 1.3×10^9 km^3 of water on Earth. They cover 70.8% of the surface, although with a much greater fraction in the SH (80.9% of the area) than the NH (60.7%), which has substantial implications for climate. Ocean currents can be >1 m s^{-1} in strong currents like the Gulf Stream, but are more typically a few cm s^{-1} at the ocean's surface. The average depth of the ocean is 3795 m. The oceans are stratified opposite to the atmosphere, with warmest waters near the surface. The cold deep abyssal ocean turns over only very slowly on time scales of hundreds to thousands of years.

Other major components of the climate system include sea ice, the land and its features (including the vegetation, albedo (reflective character), biomass, and ecosystems), snow cover, land ice (including the semi-permanent ice sheets of Antarctica and Greenland and glaciers), and rivers, lakes and surface and subsurface water. The components in the climate system (Figure 1) are shown together with the main interactions and sources of climate change.

WEATHER AND CLIMATE

For the Earth, on an annual mean basis, the excess of incoming solar radiation over outgoing longwave radiation in the tropics, and the deficit at mid to high latitudes (Figure 2), sets up an equator-to-pole temperature gradient that results, with the Earth's rotation, in a broad band of westerlies in each hemisphere in the troposphere. Embedded within the mid-latitude westerlies are large-scale weather systems which, along with the ocean, act to transport heat polewards to achieve an overall energy balance, as described below.

In the atmosphere, phenomena and events are loosely divided into the realms of "weather" and "climate". The

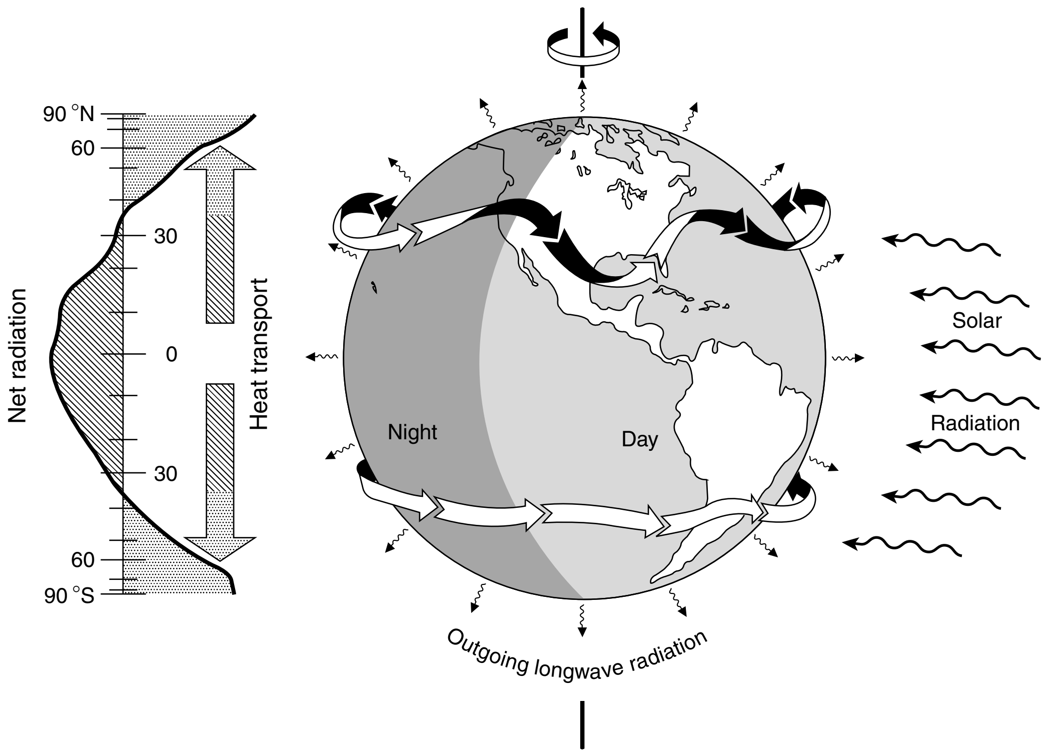

Figure 2 The incoming solar radiation (right) illuminates only part of the Earth while the outgoing longwave radiation is distributed more evenly. On an annual mean basis, the result is an excess of absorbed solar radiation over the outgoing longwave radiation in the tropics, while there is a deficit at middle to high latitudes (left), so that there is a requirement for a poleward heat transport in each hemisphere (broad arrows) by the atmosphere and the oceans. The radiation distribution results in warm conditions in the tropics but cold at high latitudes, and the temperature contrast results in a broad band of westerlies in the extratropics of each hemisphere in which there is an embedded jet stream (shown by the ribbon arrows) at about 10 km above the Earth's surface. The flow of the jet stream over the different underlying surface (ocean, land, mountains) produces waves in the atmosphere and geographic spatial structure to climate. [The excess of net radiation at the equator is $68\,W\,m^{-2}$ and the deficit peaks at $-100\,W\,m^{-2}$ at the South Pole and $-125\,W\,m^{-2}$ at the North Pole; from Trenberth and Solomon, 1994]. (From Trenberth *et al.*, 1996)

large fluctuations occurring in the atmosphere from hour-to-hour and day-to-day constitute the weather. Weather is described by such elements as temperature, air pressure, humidity, cloudiness, precipitation of various kinds and winds. Weather occurs as a wide variety of phenomena ranging from small cumulus clouds to giant thunderstorms, from clear skies to extensive cloud decks, from gentle breezes to gales, from small wind gusts to tornadoes, from frost to heat waves and from snow flurries to torrential rain. Many such phenomena occur as part of much larger-scale organized weather systems that consist, in middle latitudes, of cyclones (low pressure areas or systems) and anticyclones (high pressure systems) and their associated warm and cold fronts (*see* **Atmospheric Motions**, Volume 1). Tropical storms (referred to as hurricanes if exceeding certain intensity (64 knots or 74 miles per hour) in many regions or typhoons in the western North Pacific) are organized, large-scale systems of intense low pressure that occur in low latitudes (*see* **Hurricanes, Typhoons and other Tropical Storms – Dynamics and Intensity**, Volume 1). Weather systems migrate, develop, evolve, mature, and decay over periods of days to weeks and constitute a form of atmospheric turbulence. These weather systems arise mainly from atmospheric instabilities driven by heating patterns from the Sun and their evolution is governed by nonlinear "chaotic" dynamics, so that they are not predictable in an individual deterministic sense beyond about two weeks into the future (*see* **Chaos and Predictability**, Volume 1). Examples of weather systems are the cyclones and anticyclones and associated cold and warm fronts, which arise from the equator-to-pole temperature differences (Figure 2) and thus have their origin in the Sun–Earth geometry and the distribution of solar heating. The atmosphere responds by continual attempts to reduce those temperature gradients by producing, in the NH, southerly winds to carry warm air polewards and cold northerly winds to reduce temperatures in lower latitudes, while in the SH, the southerlies are cold and the northerly winds are warm. Another example is convection, which gives rise to the clouds and thunderstorms, driven by solar heating at the Earth's surface, that produce buoyant thermals, which rise, expand and cool, and produce rain along the way.

Climate is usually defined to be average weather and thus is thought of as the prevailing weather, which includes not just average conditions but also the range of variations. It is often described in terms of the mean and other statistical quantities that measure the variability. Climate extends over a period of time and possibly over a certain geographical region. Climate involves variations in which the atmosphere is influenced by and interacts with other parts of the climate system and the external forcings (Figure 1).

It is the sum of many weather phenomena that determines how the large-scale general circulation of the atmosphere works (i.e., the average three dimensional structure of atmospheric motion); and it is the circulation that essentially determines climate. This intimate link between weather and climate provides a basis for understanding how weather events may change as the climate changes. There are many very different weather phenomena that can take place under an unchanging climate, so a wide range of conditions occurs naturally. Consequently, even with a modest change in climate, many if not most of the same weather phenomena will still occur after the change.

This latter point can be illustrated by consideration of the mean and natural variability, and the effects of a change in the mean while leaving the variability unchanged. Many atmospheric variables, such as temperature, follow a normal (bell-shaped) frequency distribution quite closely. An example for temperature is shown in Figure 3 for a simple case where the bell-shaped distribution of anomalies of temperature, defined as departures from the mean annual cycle, is shifted to correspond to a warmer climate. For any change in mean climate, there is likely to be an amplified change in extremes. If the mean temperature is 15 °C and the standard deviation is 5 °C, 95% of the values fall within plus or minus two standard deviations, or between 5–25 °C, on a given day. Then, if the mean temperature is increased by 2.5 °C but with the same variability, there is only a small change in occurrence of temperatures near the mean. The biggest percentage change is for the extremes: the frequency of occurrence of temperatures above 25 °C increases by well over 100% while similar decreases occur

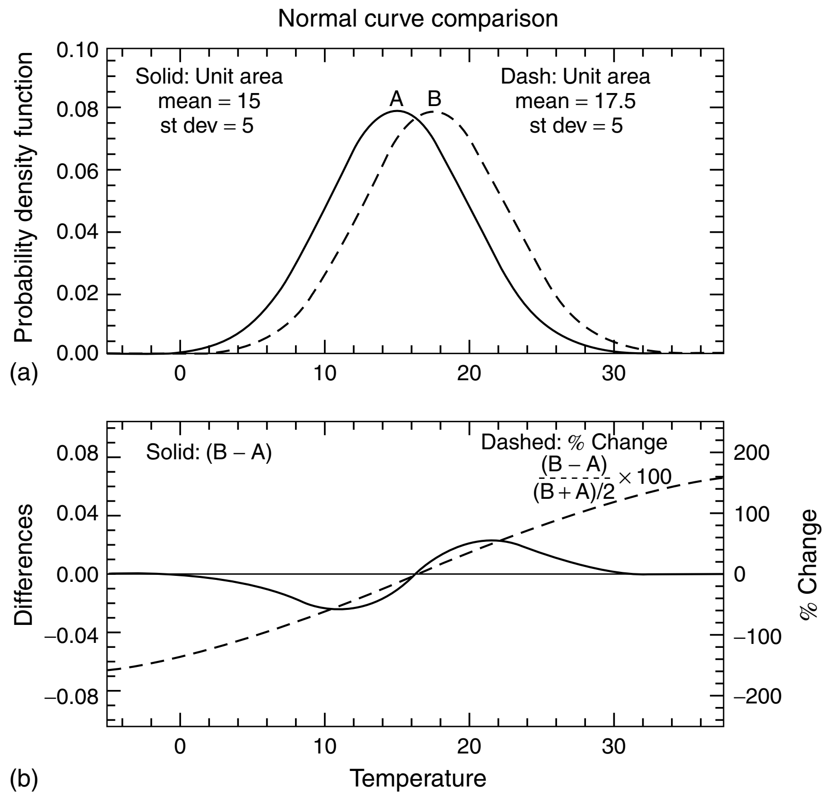

Figure 3 The two bell curves in (a) show the distribution of a climate variable (temperature in this case) before and after a climate change. The units are given in degrees Celsius. In this example, the climate change is assumed to shift the mean temperature by half a standard deviation (or 2.5 °C) but with no change in the spread of the curve (or equivalently the standard deviation, which is set to 5 °C). In (b), the differences in frequency of occurrence that result are shown as actual values (left axis) and as percentages (right axis)

for temperatures below 5 °C. The wide range of natural variability associated with day-to-day weather is the reason that we are unlikely to notice small climate changes except for the extremes.

Changes in any of the climate system components, whether internal and thus a part of the system, or from the external forcings, cause the climate to vary or to change. Thus climate can vary because of alterations in the internal exchanges of energy or in the internal dynamics of the climate system. Examples are El Niño and La Niña events, which arise from natural coupled interactions between the atmosphere and the ocean centered in the tropical Pacific. As such they are a part of the year-to-year climate and they lead to large and important systematic variations in weather patterns (events such as floods and droughts) throughout the world. Often, however, climate is taken to refer to much longer time scales – the average statistics over a 30-year period is a widespread and long-standing working definition. On these longer time scales, ENSO events vanish from mean statistics but become strongly evident in the measures of variability, such as the extremes. However, the mean climate is also influenced by the variability. These considerations become very important in the development of models of the climate system designed to serve as tools to simulate and project climate change.

THE DRIVING FORCES OF CLIMATE

The Global Energy Balance

The "shortwave" radiation from the Sun provides the source of energy that drives the climate. Much of this energy is in the visible part of the electromagnetic spectrum, although some incoming radiation extends beyond the red part of the spectrum into the infrared and some extends beyond the violet into the ultraviolet. As noted earlier, because of the roughly spherical shape of the Earth, at any one time half the Earth is in night (Figure 2). Because solar radiation is coming from just one direction, the average amount of energy incident at the top of the atmosphere is one quarter of the solar constant, or about 342 W m^{-2}. About 31% of this energy is scattered or reflected back to space by molecules, tiny airborne particles (known as aerosols) and clouds in the atmosphere, and by the Earth's surface. This leaves about 235 W m^{-2} on average to warm the Earth's surface and atmosphere (Figure 4).

To balance the incoming energy, the Earth itself must radiate, on average, the same amount of energy back to space (Figure 4). It does this by emitting thermal "longwave" radiation in the infrared part of the spectrum. The amount of thermal radiation emitted by a warm surface depends on its temperature and on how absorbing it is. For

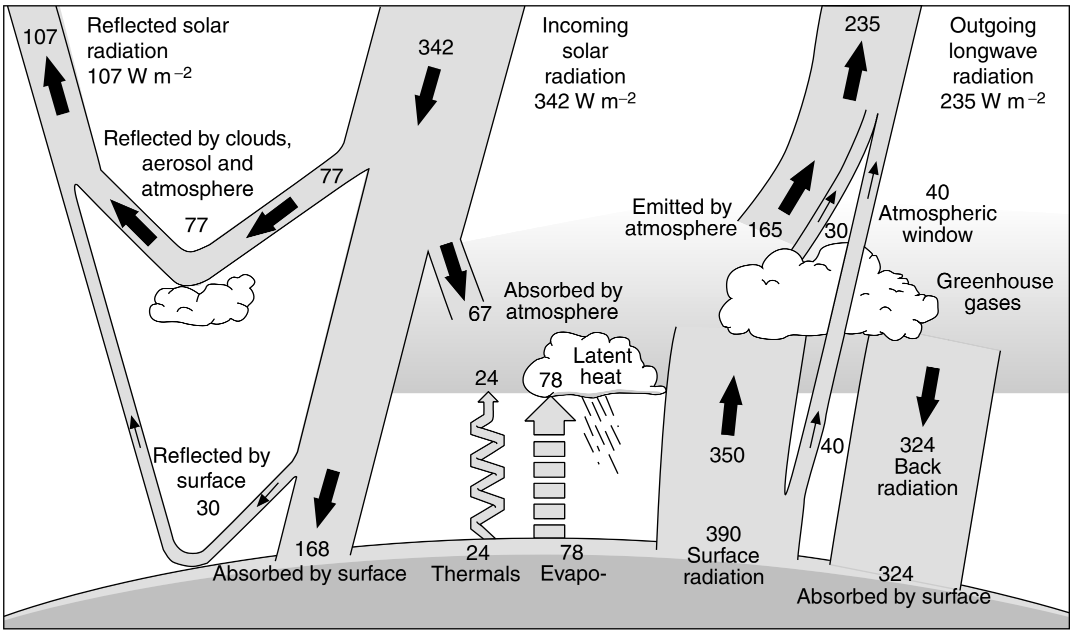

Figure 4 The Earth's radiation balance. The net incoming solar radiation of about 342 W m^{-2} is partially reflected by clouds and the atmosphere, or at the surface, but 49% is absorbed by the surface. Some of that heat is returned to the atmosphere as sensible heat and most as evapotranspiration that warms the atmosphere by release of latent heat during precipitation. The rest of the energy absorbed at the surface is radiated upward as thermal infrared radiation, most of which is absorbed by the atmosphere and re-emitted both up and down, producing a greenhouse effect because the radiation lost to space comes from cloud tops and parts of the atmosphere that are much colder than the surface. (From Kiehl and Trenberth, 1997)

a completely absorbing surface to emit 235 W m^{-2} of thermal radiation, it would have a temperature of about $-19\,^{\circ}$C. This is much colder than the conditions that actually exist near the Earth's surface, where the annual average global mean temperature is about $14\,^{\circ}$C. However, because the temperature in the troposphere falls off quite rapidly with height, a temperature of $-19\,^{\circ}$C is reached typically at an altitude of about 5 km above the surface in mid-latitudes. This provides a clue about the role of the atmosphere in making the surface climate warmer and thereby hospitable (*see* **Energy Balance and Climate**, Volume 1).

The Greenhouse Effect

Some of the infrared radiation leaving the atmosphere originates at or near the Earth's surface and is transmitted relatively unimpeded through the atmosphere; this is the radiation from areas where there are no clouds and which is emitted in the part of the spectrum known as the atmospheric "window" (Figure 4). The bulk of the radiation emitted from the surface, however, is intercepted and re-emitted both up and down. The emissions to space occur either from the tops of clouds at different atmospheric levels (which are almost always colder than the surface), or by gases present in the atmosphere that absorb and emit infrared radiation. Most of the atmosphere consists of nitrogen and oxygen (composing about 99% of dry air), which are transparent to infrared radiation. It is the water vapor, which varies in amount from 0 to about 3%, carbon dioxide and some other minor gases present in the atmosphere in much smaller quantities that absorb some of the thermal radiation leaving the surface and re-emit radiation from much higher and colder levels out to space. These radiatively active gases are known as greenhouse gases because they act as a partial blanket for the thermal radiation from the surface and enable the surface to be substantially warmer than it would otherwise be, analogous to the effects of a greenhouse. (While a real greenhouse does work this way, the main heat retention in a greenhouse comes through protection from the wind.) This blanketing is known as the natural greenhouse effect. In the current climate under clear sky conditions, water vapor is estimated to account for about 60% of the greenhouse effect, carbon dioxide 26%, ozone 8% and other gases 6% (Kiehl and Trenberth, 1997) (*see* **Greenhouse Effect**, Volume 1).

Effects of Clouds

Clouds also absorb and emit thermal radiation; as a result, they have a blanketing effect similar to that of the greenhouse gases. However, clouds are also bright reflectors of solar radiation and thus also act to cool the surface. While on average there is strong cancellation between the two opposing effects of shortwave and longwave cloud heating, the net global effect of clouds in our current climate, as determined by space-based measurements, is a small cooling of the surface. A key issue is how clouds will change as climate changes. This issue is complicated by the fact that clouds are also strongly influenced by particulate pollution, which tends to lead to much smaller cloud droplets, and thus makes clouds brighter and more reflective of solar radiation. These effects may also influence the timing and amounts of precipitation. In addition, if cloud altitude changes, the climate can be affected. If cloud tops get higher, the radiation to space from clouds is at a colder temperature and so this reduction in the loss of the energy from the Earth produces a warming influence. However, more extensive low clouds would be likely to produce cooling because of their high reflectivity and so their greater influence on solar radiation.

The Hydrological Cycle

The Earth contains roughly 1.3×10^9 km^3 of water. Slightly more than 97% of the water is in the oceans and is therefore salty. The fresh water in rivers, lakes, glaciers, and underground aquifers make up roughly 36×10^6 km^3 of water. About 220 000 km^3 of fresh water is in the lakes and rivers and 12 000 km^3 is in the atmosphere. Of the fresh water, 28×10^6 km^3 is locked up frozen in ice sheets, ice caps and glaciers. Most of the ice is contained in the Antarctic ice sheet which, if melted, would increase sea level by about 65 m. By contrast, Greenland contains the equivalent of about 7 m of sea level and the other glaciers and ice caps contain about 0.5 m (*see* **Glaciers**, Volume 1). Most of the remaining 8×10^6 km^3 of fresh water is stored underground as ground water (*see* **Hydrologic Cycle**, Volume 1).

The hydrological cycle involves the transfer of water from the oceans to the atmosphere, to the land and back to the oceans, both on top of and beneath the land surface. Water is evaporated from the ocean surface, and as water vapor it is typically transported thousands of kilometers before it is taken up in clouds and weather systems and is precipitated out as rain, snow, hail or some other frozen pellet back to the Earth's surface. Over land, some precipitation infiltrates or percolates into soils and some runs off into streams and rivers. Ponds and lakes or other surface water may evaporate moisture into the atmosphere, and can also freeze so that water can become locked up for a while. The surface water weathers rocks and erodes the landscape, and replenishes subterranean aquifers. Over land, plants transpire moisture into the atmosphere.

A schematic view of the cycling of water through the climate system is given in Figure 5. This figure not only shows the main water reservoirs and the amounts in each in units of 10^3 km^3, but also gives the volumetric flows between ocean, land and atmosphere (based on results from Trenberth and Guillemot, 1998). In units of 10^3 km^3 per

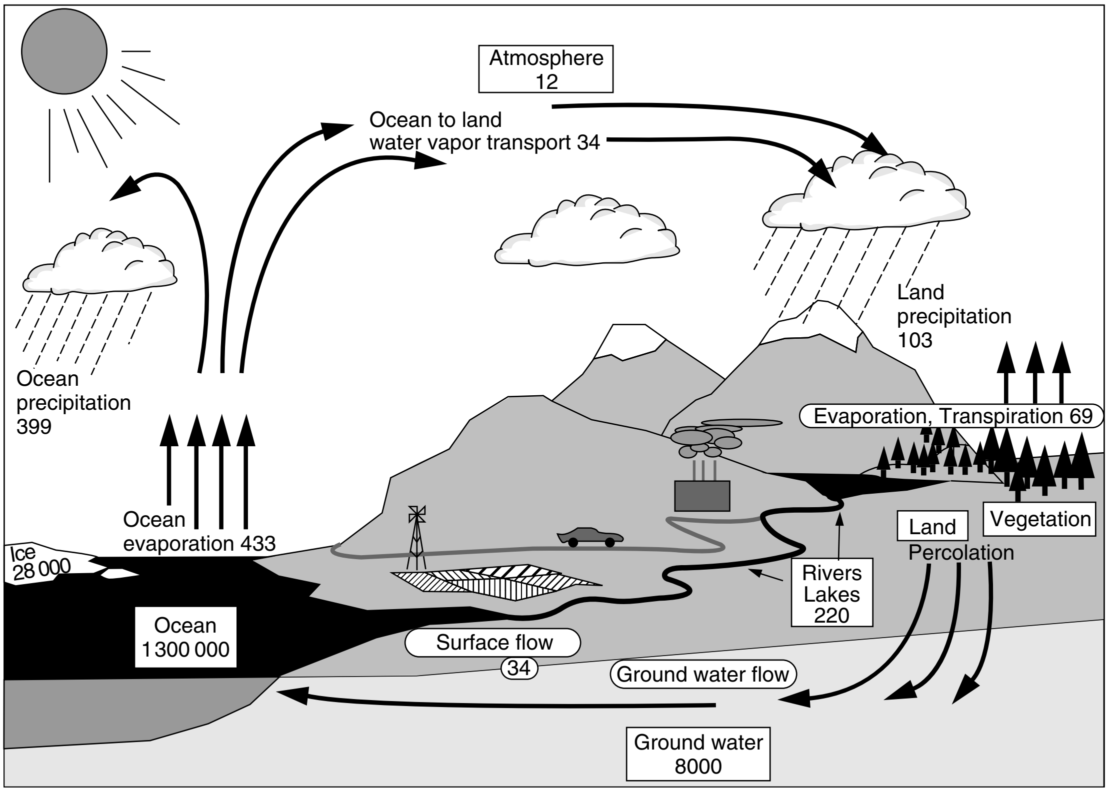

Figure 5 The hydrological cycle, showing the reservoirs of water in square boxes and amounts in units of 10^3 km^3. The figure also shows the flows of water between reservoirs (in oval boxes) in units of 10^3 km^3 year^{-1}

year, evaporation over the oceans (433) exceeds precipitation (399), leaving a net of 34 units of moisture transported onto land as water vapor. On average, this flow must be balanced by a return flow over and beneath the ground through river and stream flows, and subsurface ground water flow. Consequently, precipitation over land exceeds evapotranspiration by this same amount (34). Not surprisingly, perhaps, the average precipitation rate over the oceans exceeds that over land by 72% (allowing also for the differences in areas). It has been estimated (Trenberth, 1998) that on average over 80% of the moisture precipitated out comes from locations over 1000 km distant, highlighting the important role of the winds in moving moisture around.

The Role of Oceans

The oceans cover 70% of the Earth's surface and through their fluid motions, their high heat capacity, and their ecosystems play a central role in shaping the Earth's climate and its variability. The most important characteristic of the oceans is that they are wet and, while obvious, this is sometimes overlooked. Water vapor, evaporated from the ocean surface, provides latent heat energy to the atmosphere during the precipitation process. Wind blowing on the sea surface drives the large-scale ocean circulation in its upper layers. The ocean currents carry heat and salt along with the fresh water around the globe (*see* **Ocean Circulation**, Volume 1; **Salinity Patterns in the Ocean**, Volume 1). The oceans therefore store heat, absorbed at the surface, for varying durations and release it in different places, thereby ameliorating temperature changes over nearby land and contributing substantially to variability of climate on many time scales. Additionally, the ocean thermohaline circulation (*see* **Thermohaline Circulation**, Volume 1), which is the circulation driven by changes in sea water density arising from temperature (thermal) or salt (haline) effects, allows water from the surface to be carried into the deep ocean, where it is isolated from atmospheric influence and hence it may sequester heat for periods of a thousand years or more. The oceans also absorb carbon dioxide and other gases and exchange them with the atmosphere in ways that change with ocean circulation and climate change. In addition, it is likely that marine biotic responses to climate change will result in subsequent changes that may have further ramifications.

The Role of Land

The heat penetration into land occurs mainly through conduction, except where water plays a role, so that heat penetration is limited and slow. Temperature profiles taken from bore holes into land or ice caps therefore provide a blurry coarse estimate of temperatures in years long past (see Pollack *et al.*, 1998 and **Ground Temperature**, Volume 1). Consequently, surface air temperature changes over land occur much faster and are much larger than over the oceans for the same heating and, because we live on land, this directly affects human activities.

The land surface encompasses an enormous variety of topographical features and soils, differing slopes (which influence runoff and radiation received) and water capacity. The highly heterogeneous vegetative cover is a mixture of natural and managed ecosystems that vary on very small spatial scales. Changes in soil moisture affect the disposition of heat at the surface and whether it results in increases in air temperature or increased evaporation of moisture. The latter is complicated by the presence of plants, which can act to pump moisture out of the root zone into the leaves, where it can be released into the atmosphere as the plant participates in photosynthesis; a process called *transpiration*. The behavior of land ecosystems can be greatly influenced by changes in atmospheric composition and climate. The availability of surface water and the use of the Sun's energy in photosynthesis and transpiration in plants influence the uptake of carbon dioxide from the atmosphere as plants transform the carbon and water into usable food. Changes in vegetation alter how much sunlight is reflected and how rough the surface is in creating drag on the winds, and the land surface and its ecosystems play an important role in the carbon cycle and fluxes of water vapor and other trace gases.

The Role of Ice

Major ice sheets, like those over Antarctica and Greenland, have a large heat capacity but, like land, the penetration of heat occurs primarily through conduction so that the mass experiencing temperature changes from year to year is small. Temperature profiles can be taken directly from boreholes into ice (see Dahl-Jensen *et al.*, 1998 for temperatures directly from boreholes in the Greenland ice sheet). The temperature profiles suggest that the upward heat flow from the underlying ground is about 51 $\mathrm{mW\,m^{-2}}$, which is very small compared to the various components of the Earth's energy balance. On century timescales, however, the ice sheet heat capacity becomes important. Unlike land, the ice can melt, which has major consequences on longer timescales through changes in sea level.

A major concern has been the possible instability of the West Antarctic Ice Sheet (WAIS) because it is partly grounded below sea level. At the present rate of accumulation, the time needed to restore the ice is estimated as over 10 000 years (Oppenheimer, 1998) so that changes are very slow and occur on millennial time scales unless an instability arises (*see also* **Antarctica**, Volume 1). If warming alters the grounding of the ice sheet, making it float, it becomes more vulnerable to rapid disintegration, ultimately leading to a rise in sea level of 4–6 m. The present assessment by Oppenheimer is that the risk of substantial change in WAIS contributing to major sea level rise in the 21st century is small, but the risk increases in future centuries as human-induced global climate change progresses. However, there is concern that, after a certain critical point is reached, such changes may be irreversible and unstoppable once begun.

Sea ice is an active component of the climate system and varies greatly in areal extent with the seasons, but only at higher latitudes (*see* **Sea Ice**, Volume 1). In the Arctic where sea ice is confined by the surrounding continents, mean sea ice thickness is 3–4 m thick and multi-year ice can be present. Around Antarctica the sea ice is unimpeded and spreads out extensively, but as a result the mean thickness is typically 1–2 m.

The Role of Heat Storage

The different components of the climate system contribute on different timescales to climate variations and change. The atmosphere and oceans are fluid systems and can move heat around through convection and advection (in which the heat is carried by the currents, whether small-scale short-lived eddies or large-scale atmospheric jet streams or ocean currents). Changes in phase of water, from ice to liquid to water vapor, affect the storage of heat. However, even ignoring these complexities, many facets of the climate can be deduced simply by considering the heat capacity of the different components of the climate system. The total heat capacity considers the mass involved as well as its capacity for holding heat, as measured by the specific heat of each substance.

The atmosphere does not have much capability to store heat. The heat capacity of the global atmosphere corresponds to that of only a 3.2 m layer of the ocean. However, the depth of ocean actively involved in climate is much greater than that. The specific heat of dry land is roughly a factor of 4.5 less than that of sea water (for moist land the factor is probably closer to 2). Moreover, heat penetration into land is limited by the low thermal conductivity of the land surface; as a result only the top two meters or so of the land typically play an active role in heat storage and release (e.g., as the depth for most of the variations over annual time scales). Accordingly, land plays a much smaller role than the ocean in the storage of heat and in providing a memory for the climate system. Similarly, the ice sheets and glaciers do not play a strong role, while sea ice is important where it forms.

The seasonal variations in heating penetrate into the ocean through a combination of radiation, convective overturning (in which cooled surface waters sink while warmer more buoyant waters below rise) and mechanical stirring by winds. These processes mix heat through what is called the *mixed layer*, which, on average, involves about the upper 90 m of ocean. The thermal inertia of the 90 m layer can add a delay of about 6 years to the temperature response to an instantaneous change (this time corresponds to an exponential time constant in which there is a 63% response toward a new equilibrium value following an abrupt change). As a result, actual changes in climate tend to be gradual. With its mean depth of about 3800 m, the total ocean would add a delay of 230 years to the response if rapidly mixed. However, mixing is not a rapid process for most of the ocean so that in reality the response depends on the rate of ventilation of water between the well-mixed upper layers of the ocean and the deeper, more isolated layers that are separated by the thermocline (ocean layer, below the mixed layer, exhibiting a strong vertical temperature gradient). The rate of such mixing is not well established and varies greatly geographically. An overall estimate of the delay in surface temperature response caused by the oceans is 10–100 years. The slowest response should be in high latitudes where deep mixing and convection occur, and the fastest response is expected in the tropics. Consequently, the oceans are a great moderating effect on climate changes, especially changes such as those involved with the annual cycle of the seasons.

Generally, the observed variability of temperatures over land is a factor of two to six greater than that over the oceans. At high latitudes over land in winter there is often a strong surface temperature inversion whose strength is very sensitive to the amount of stirring in the atmosphere (Trenberth, 1993). Such wintertime inversions are significantly affected by human activities; for instance an urban heat island effect exceeding 10 °C has been observed during strong surface inversion conditions in Fairbanks, Alaska. Strong surface temperature inversions over mid-latitude continents also occur in winter. In contrast, over the oceans, surface fluxes of heat into the atmosphere keep the air temperature within a narrow range. Thus it is not surprising that over land, month-to-month persistence in surface temperature anomalies is greatest near bodies of water. Consequently, it is clear that for a given heating perturbation, the response over land should be much greater than over the oceans; the atmospheric winds are the reason why the observed factor is only in the two to six range.

A further example of the role of the oceans in moderating temperature variations is the contrast in the mean annual cycle of surface temperature between the NH (60.7% water) and SH (80.9% water) (Figure 6). The amplitude of the 12-month cycle between 40 and 60 °latitude ranges from <3 °C in the SH to ~12 °C in the NH. Similarly, in mid-latitudes from 22.5–67.5 °latitude, the average lag in temperature response relative to peak solar radiation is 32.9 days in the NH versus 43.5 days in the SH (Trenberth, 1983),

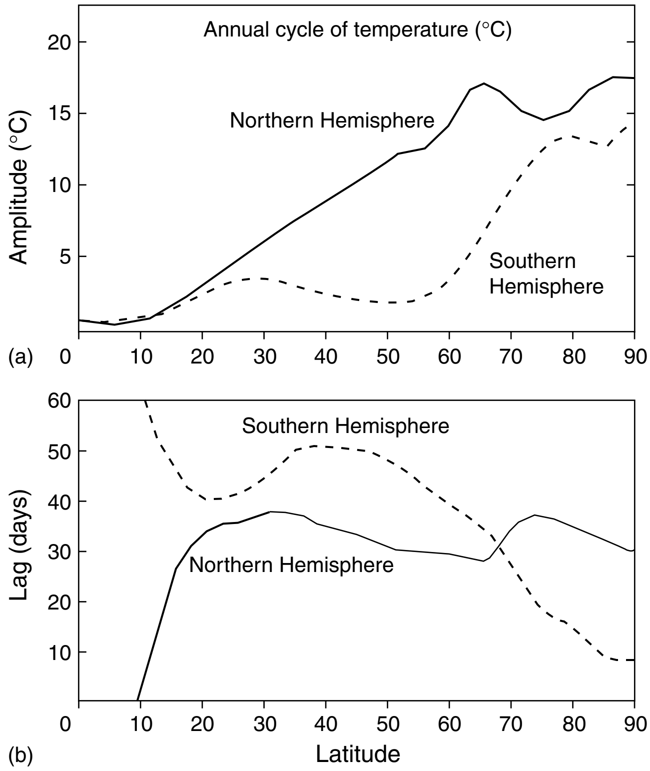

Figure 6 Amplitude of the annual cycle in zonal mean surface temperatures in °C as a function of latitude (a), and the lag of the temperature response behind the Sun in days (b). (From Trenberth, 1983)

again reflecting the difference in thermal inertia. Even the sea surface temperatures (SSTs) in the two hemispheres undergo quite different amplitudes in the annual cycle, and average SSTs are higher in the NH versus the SH at each latitude because of the land distribution and the winds that blow from land to ocean.

Atmosphere–Ocean Interaction: El Niño

Understanding the climate system becomes more complex as the components interact. El Niño events are a striking example of a phenomenon that would not occur without interactions between the atmosphere and ocean. El Niño events involve a warming of the surface waters of the tropical Pacific Ocean (*see* **El Niño and La Niña: Causes and Global Consequences**, Volume 1). Ocean warming takes place from the International Dateline to the west coast of South America and results in changes in the local and regional ecology. Historically, El Niño events have occurred about every 3–7 years and alternated with the opposite phases of below average temperatures in the tropical Pacific, dubbed La Niña. In the atmosphere, a pattern of change called the Southern Oscillation is closely linked with these ocean changes, so that scientists refer to the total phenomenon as ENSO (*see* **El Niño/Southern**

Oscillation (ENSO), Volume 1). Then El Niño is the warm phase of ENSO and La Niña is the cold phase.

The strong SST gradient from the warm pool in the western tropical Pacific to the cold tongue in the eastern equatorial Pacific is maintained by the westward-flowing trade winds, which drive the surface ocean currents and determine the pattern of upwelling of cold nutrient-rich waters in the east. Because of the Earth's rotation, easterly winds along the equator deflect currents to the right in the NH and to the left in the SH and thus away from the equator, creating upwelling along the equator. Low sea-level pressures are set up over the warmer waters while higher pressures occur over the cooler regions in the tropics and subtropics. The moisture-laden winds tend to blow toward low pressure so that the air converges, resulting in organized patterns of heavy rainfall and a large-scale overturning along the equator called the Walker Circulation (*see* **Walker Circulation**, Volume 1). Because convection and thunderstorms preferentially occur over warmer waters, the pattern of SSTs determines the distribution of rainfall in the tropics, and this in turn determines the atmospheric heating patterns through the release of latent heat. The heating drives the large-scale monsoonal-type circulations in the tropics, and consequently determines the winds.

If the Pacific trade winds relax, the ocean currents and upwelling change, causing temperatures to increase in the east, which decreases the surface pressure and temperature gradients along the equator, and so reduces the winds further. This positive feedback leads to the El Niño warming persisting for a year or so, but the ocean changes also sow the seeds of the event's demise. The changes in the ocean currents and internal waves in the ocean lead to a progression of colder waters from the west that may terminate the El Niño and lead to the cold phase La Niña in the tropical Pacific. The El Niño develops as a coupled ocean–atmosphere phenomenon and, because the amount of warm water in the tropics is redistributed, depleted and restored during an ENSO cycle, a major part of the onset and evolution of the events is determined by the history of what has occurred one to two years previously. This means that the future evolution is potentially predictable for several seasons in advance.

The changes in atmospheric circulation are not confined to the tropics but extend globally and influence the jet streams and storm tracks in mid-latitudes. For El Niño conditions, higher than normal sea level pressures over Australia, Indonesia, Southeast Asia, and the Philippines signal drier conditions or even droughts. Dry conditions also prevail for Hawaii, parts of Africa, and extend to the northeast part of Brazil and to Colombia. Intense rains prevail over the central and eastern Pacific, along the west coast of South America and over parts of South America near Uruguay and southern parts of the United States in winter.

OBSERVED CLIMATE CHANGE

Global aspects

We usually view the climate system from our perspective as individuals on the surface of the Earth. Just a few decades ago, the only way a global perspective could be obtained was by collecting observations of the atmosphere and the Earth's surface made at points over the globe and analyzing them to form maps of various fields, such as temperatures. The observational coverage has increased over time, but even today it is not truly global because of the sparse observations over the southern oceans and the polar regions. Earth observing satellites have changed this, as two polar-orbiting sun-synchronous satellites can provide global coverage in about six hours, and geostationary satellites provide images of huge portions of the Earth almost continuously (*see* **Earth Observing Systems**, Volume 1). The satellites have revealed the myriad cloud types and patterns of infinite variety, and glimpses of the surface underneath. Over land, changes in vegetation and snow cover with the seasons and from year to year can be seen. However, it is difficult to see below the ocean surface and observations in the ocean domain remain few and far between.

In the more distant past, instrumental observations are not available at all and the nature of the weather and climate has to be estimated from proxy indicators (*see* **Natural Records of Climate Change**, Volume 1). These are organisms that are known to be sensitive to changes in temperature and precipitation, such as trees (through the width and composition of annual tree rings), corals (through annual layers in coral colonies), glaciers (through annual layers of snow and ice), and deposits of small organisms and pollen from plants or land dust on the bottoms of lakes and in marine sediments in oceans. Such fossil indicators can give some estimate of past climate, although the geographical coverage diminishes rapidly the further back in time we go because the most recent ice age obliterates the evidence of the earlier ones.

Even for instrumental observations, the long time-series of high quality observations needed to discern small changes are often compromised by spurious effects, and special care is required in interpretation. Most observations have been made for other purposes, such as weather forecasting, and therefore typically suffer from changes in instrumentation, instrument exposure, measurement techniques, station location and observation times, and in the general environment (such as the building of a city around the measurement location) and there have been major changes in distribution and numbers of observations. Adjustments must be devised to take into account all these influences in estimating the real changes that have occurred.

Analysis of observations of surface temperature show that there has been a global mean warming of about 0.7 °C

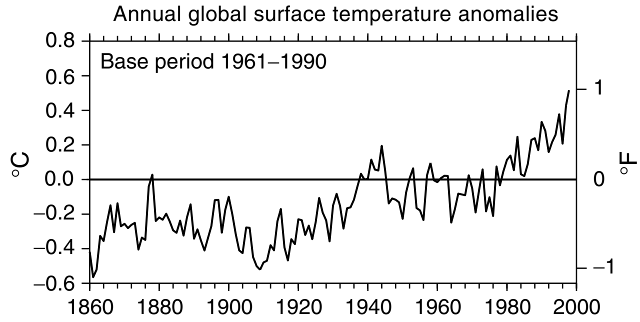

Figure 7 Global annual mean temperatures from 1860–1998 as departures from the 1961–1990 means. (Courtesy Jim Hurrell, adapted from data provided by Hadley Centre, UKMO, and Climate Research Unit, University East Anglia)

over the past one hundred years (*see* **The Global Temperature Record**, Volume 1); see Figure 7 for the instrumental record of global mean temperatures. The warming became noticeable from the 1920s to the 1940s, leveled off from the 1950s to the 1970s and took off again in the late 1970s. The calendar year 1998 was by far the warmest on record, exceeding the previous record held by 1997. The 1990s were the warmest decade on record. Information from paleodata further indicates that these years are the warmest in at least the past 1000 years, which is as far back as a hemispheric estimate of temperatures can be made (Mann *et al.*, 1999 and *see* **Little Ice Age**, Volume 1; **Medieval Climatic Optimum**, Volume 1). The melting of glaciers over most of the world and rising sea levels confirm the reality of the global temperature increases. The observed trend for a larger increase in minimum than maximum temperatures is linked to the associated increases in low cloud amount and aerosol as well as the enhanced greenhouse effect (Dai *et al.*, 1998). There is good evidence for decadal changes in the atmospheric circulation and some evidence for ocean changes. Changes in precipitation and other components of the hydrological cycle vary considerably geographically. Changes in climate variability and extremes are beginning to emerge, but global patterns are not yet apparent.

Changes in climate have occurred in the distant past as the distribution of continents and their landscapes have changed, as the so-called Milankovitch changes in the orbit of the Earth and the Earth's tilt relative to the ecliptic plane have varied the insolation received on Earth, and as the composition of the atmosphere has changed, all through natural processes (*see* **Earth System History**, Volume 1; **Orbital Variations**, Volume 1). Recent evidence from ice cores drilled through the Greenland ice sheet (e.g., Bond *et al.*, 1997) have indicated that changes in climate may often have been quite rapid and large, and not associated with any known external forcings (*see* **Climate Change, Abrupt**, Volume 1). Understanding the spatial scales of this variability and the processes and mechanisms involved is very important as it seems quite possible that strong non-linearities may be involved that result in large changes from relatively small perturbations by provoking positively reinforcing feedback processes in the internal climate system. Changes in the thermohaline circulation in the Atlantic Ocean are one way such abrupt changes might be realized (*see* **Thermohaline Circulation**, Volume 1). An important question therefore is whether there might be prospects for major surprises as the climate changes.

Spatial Structure of Climate and Climate Change

Because of the land/ocean contrasts and obstacles such as mountain ranges, the mid-latitude westerly winds and the embedded jet stream in each hemisphere contain planetary-scale waves (Figure 2). These waves are usually geographically anchored but can change with time as heating patterns change in the atmosphere. A consequence is that anomalies in climate on a seasonal time scales typically occur over large geographic regions with surface temperatures both above and below normal in different places. The same is true even on much longer time scales. Figure 8 shows that the recent warming has been largest over most of the northern continents, much less over the eastern half of the US, and with cooling over the North and South Pacific and North Atlantic (Trenberth and Hurrell, 1994; Hurrell, 1996; Trenberth and Hoar, 1996, 1997). These changes are known to be dominant in the northern winter and associated with changes in the atmospheric circulation and influences such as El Niño. On a year by year basis, extensive regions of both above and below normal temperatures are the rule, not the exception, as should clearly be expected from the wave motions in the atmosphere.

Temperatures vary enormously on all space and time scales. At individual locations there is a large diurnal cycle, e.g., at Boulder, Colorado (at 40 °N in the central US) from −7 °C to +7 °C in early January and 15 °C to 30 °C in mid-July. There is also a large annual cycle in daily-average temperature, in this case a 23 °C range. The standard deviation is a measure of the variability. A rule of thumb is that 95% of values fall within ±2 times the standard deviation and 68% of the values fall within ±1 standard deviation of the mean. The standard deviation of daily temperature anomalies at Boulder is 4.5 °C while for monthly means, the value drops to 2.1 °C as the vagaries of day to day weather are averaged out. Note that for the daily values, in this case, 71% fall within ±1 standard deviation of the mean and there are some extreme values well outside ±2 standard deviations. Both situations arise from the annual cycle, which exhibits much less variability in summer and much greater variability in winter. Spatial averages also average out the pluses and minuses, as illustrated in Figure 9, which presents the

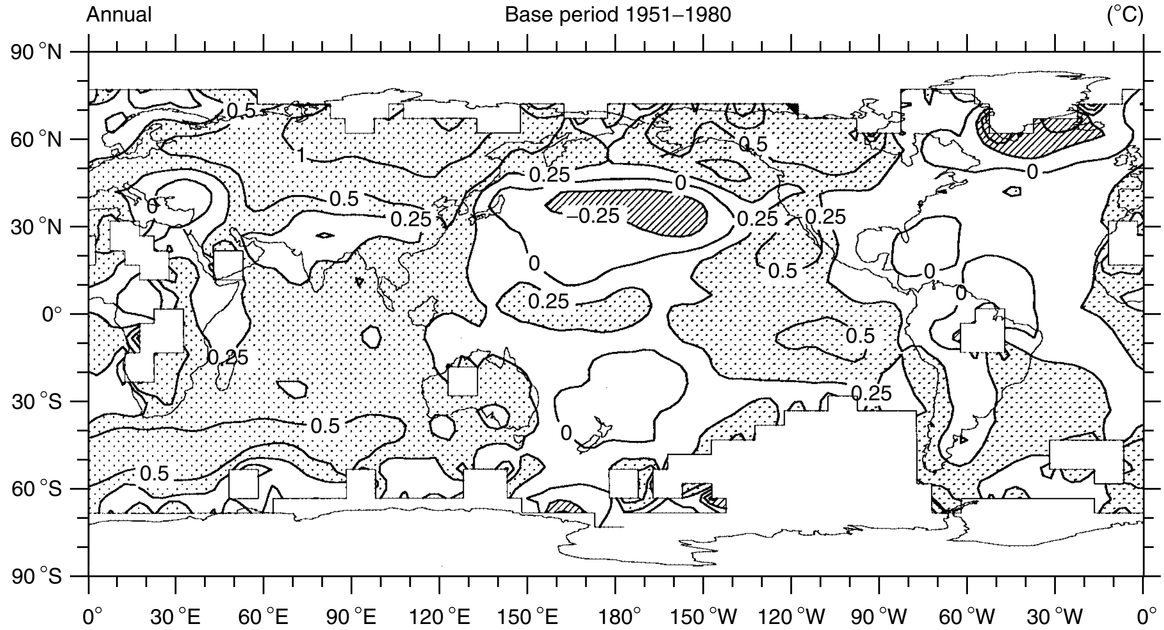

Figure 8 Annual mean surface temperature anomalies for the period 1981–1997 relative to a baseline set of temperatures for 1951–80 . (Courtesy J. Hurrell, adapted from data provided by Hadley Centre, UKMO, and CRU, University East Anglia)

monthly temperature anomalies for Boulder, Colorado, the US, and the globe. For the US as a whole the standard deviation is 1.2 °C and for the globe it is 0.24 °C. Only in the latter is the global warming really apparent. It becomes even clearer in yearly averages (Figure 7).

Figure 9 shows that small trends in global mean values are not readily perceived in regional or local values, simply because of the large natural weather-related variability; this has implications for predictability. The latter depends on the size of the signal from some climate forcing versus the noise of natural variability. As indicated above, the noise (variability) is large locally but can be reduced by spatial and temporal averaging. Consequently, random weather variations mean that local predictions for a month are less reliably determined than averages over large areas and over longer times.

ANTHROPOGENIC CLIMATE CHANGE

Human Influences

Climate can vary for multiple reasons and, in particular, human activities can lead to changes in several ways. There have been major changes in land use over the past two centuries. Conversion of forest to cropland, in particular, has led to a higher albedo in places such as the eastern and central US and changes in evapotranspiration, both of which have probably cooled the region, in summer by perhaps 1 °C and especially in autumn by more than 2 °C, although global effects are less clear (Bonan, 1997, 1999). In cities, the building of "concrete jungles" allows heat to be soaked up and stored during the day and released at night, moderating nighttime temperatures and contributing to an urban heat island. Space heating also contributes to this effect. Urbanization changes also affect the runoff of water, leading to drier conditions unless compensated by the cooling influences of water usage and irrigation. However, these influences, while causing real changes in urban areas, are quite local. Widespread irrigation on farms can have more regional effects, and so management and storage of water in general is important.

Combustion of fossil fuels not only generates carbon dioxide and heat, but also generates particulate pollution (e.g., soot, smoke) as well as gaseous pollution that can become particulates (e.g., sulfur dioxide, nitrogen dioxide; which get oxidized to form tiny sulfate and nitrate particles) (*see* **Aerosols, Troposphere**, Volume 1). Other gases, such as carbon monoxide, are also formed in burning and, as a result, the composition of the atmosphere is changing. Several other gases, notably methane, nitrous oxide, the chlorofluorocarbons (CFCs) and tropospheric ozone are also observed to have increased from human activities (especially from biomass burning, landfills, rice paddies, agriculture, animal husbandry, fossil fuel use, leaky fuel lines, and industry), and these are all greenhouse gases. However, the observed decreases in lower stratospheric ozone since the 1970s (*see* **Stratosphere, Ozone Trends**, Volume 1), caused principally by human-introduced CFCs and halons, contribute to a small cooling in that region (Intergovernmental Panel on Climate Change (IPCC), 1994).

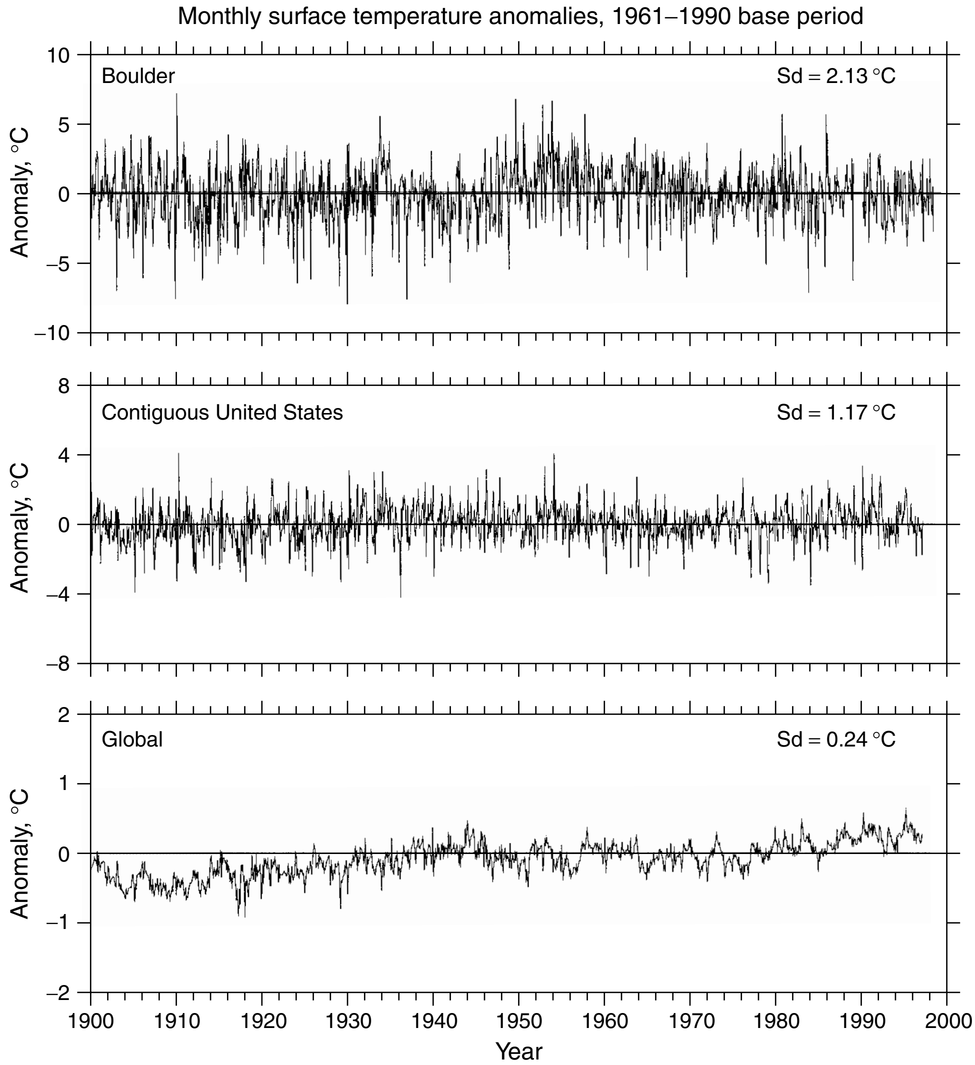

Figure 9 Monthly temperature anomalies for Boulder, Colorado, the US and the globe. The standard deviations (Sd) are listed as 2.13 °C for Boulder, 1.17 °C for the US and 0.24 °C for the globe. The anomalies, defined as departures from the mean annual cycle, are relative to the 1961–90 base period

The Enhanced Greenhouse Effect

The amount of carbon dioxide in the atmosphere has increased by more than 30% over the past two centuries since the beginning of the Industrial Revolution, an increase that is known to be due largely to combustion of fossil fuels and the removal of forests (*see* **Carbon Dioxide, Recent Atmospheric Trends**, Volume 1). Most of this increase has occurred since World War II. Because carbon dioxide is recycled through the atmosphere many times before it is finally removed from the active atmosphere-ocean-vegetation resevoirs, the excess concentration has a lifetime exceeding a hundred years. As a result, continuing emissions will lead to a continuing build-up in the atmospheric concentrations. In the absence of controls, future projections are that the rate of increase in carbon dioxide emissions (*see* **Trends in Global Emissions: Carbon, Sulfur, and Nitrogen**, Volume 3) may accelerate and concentrations could double their pre-industrial values within the next sixty or so years (IPCC, 1994). Effects of implementing the Kyoto Protocol of 1997 (*see* **United Nations Framework Convention on Climate Change and Kyoto Protocol**, Volume 4) are quite uncertain but may delay doubling of pre-industrial values by perhaps 15 years (Wigley, 1998), and thus would buy time but would not solve the problem.

Effects of Aerosols

Human activities also affect the amount of aerosol in the atmosphere, which influences climate in other ways. The main direct effect of aerosols is the scattering of some solar radiation back to space; which tends to cool the Earth's surface. Aerosols can also influence the radiation budget by directly absorbing solar radiation leading to local heating of the atmosphere and, to a lesser extent, by absorbing and emitting thermal radiation. A further influence of aerosols is that many of them act as nuclei on which cloud droplets condense. A changed concentration therefore tends to affect the number and size of droplets in a cloud and hence alters the reflection and the absorption of solar radiation by the cloud. Recent evidence highlights the possible importance of this effect, although the magnitude is very uncertain (Hansen *et al.*, 1997 and *see* **Aerosols, Effects on the Climate**, Volume 1).

Aerosols occur in the atmosphere from natural causes; for instance, they are blown off the surface of deserts or dry regions. The eruption of Mt. Pinatubo in the Philippines in June 1991 added considerable amounts of aerosol to the stratosphere (*see* **Aerosols, Stratosphere**, Volume 1; **Volcanic Eruption, Mt. Pinatubo**, Volume 1), which for about two years, scattered solar radiation leading to a loss of radiation at the surface and a cooling there. Human activities contribute to aerosol particle formation mainly through injection of sulfur dioxide into the atmosphere (which contributes to acid rain) particularly from power stations and through biomass burning.

Because aerosols resulting from human activities typically remain in the atmosphere for only a few days, they tend to be concentrated near their sources, such as near and downwind of industrial regions. The cooling therefore exhibits a very strong regional pattern, and the presence of aerosols adds further complexity to possible climate change as it can help mask, at least temporarily, global warming arising from increased greenhouse gases. However, the aerosol effects do not cancel the global-scale effects of the much longer-lived greenhouse gases, and significant climate changes can still result.

CLIMATIC RESPONSE

Feedbacks

We use the global warming as a specific example of climate change to highlight the issues of determining a climatic response to a particular climate forcing. Determining the climatic response to a change in the radiative forcing is complicated by feedbacks. Some of these can amplify the original warming (positive feedback) while others serve to reduce it (negative feedback) (*see* **Climate Feedbacks**, Volume 1).

If, for instance, the amount of carbon dioxide in the atmosphere were suddenly doubled, but with other things remaining the same, the outgoing long-wave radiation would be reduced by about $4\,\mathrm{W\,m^{-2}}$ and this energy would be trapped in the surface–atmosphere system. To restore the radiative balance, the surface–atmosphere system must warm up. In the absence of other changes, the warming at the surface and throughout the troposphere would be about 1.2 °C. In reality, many other factors will change, and various feedbacks come into play, so that the best estimate of the average global warming for doubled carbon dioxide is 2.5 °C (IPCC, 1990, 1995). In other words the net effect of the feedbacks is positive and roughly doubles the response otherwise expected.

Increased heating therefore leads naturally to expectations for increases in global mean temperatures (often mistakenly thought of as "global warming"), but other changes in weather are also important. Increases in greenhouse gases in the atmosphere produce global warming through an increase in downwelling infrared radiation, and thus not only increase surface temperatures but also enhance the hydrological cycle because much of the heating at the surface goes into additional evaporation of surface moisture. Global temperature increases signify that the water-holding capacity of the atmosphere increases and, together with enhanced evaporation, this means that the actual atmospheric moisture increases (*see* **Water Vapor: Distribution and Trends**, Volume 1), as is observed to be happening in many places (Trenberth, 1998). It follows that naturally occurring droughts are likely to be exacerbated by enhanced drying. Thus droughts, such as those set up by El Niño, are likely to start sooner, plants will wilt sooner, and the droughts may become more extensive and last longer with global warming. Once the land is dry, then all the solar radiation goes into raising temperature, bringing on sweltering heat waves.

Further, globally there must be an increase in precipitation to balance the enhanced evaporation. The presence of increased moisture in the atmosphere implies stronger moisture flow converging into all precipitating weather systems, whether they are thunderstorms, or extratropical rain or snowstorms. This leads to the expectation of enhanced rainfall or snowfall events, which is also observed to be happening (Karl and Knight, 1998; Trenberth, 1998).

The main positive feedback thus comes from water vapor as the amount of water vapor in the atmosphere increases as the Earth warms and, because water vapor is an important greenhouse gas, it amplifies the warming. However, increases in cloud may act either to amplify the warming through the greenhouse effect of clouds or reduce it by the increase in albedo; which effect dominates depends on the height and type of clouds, and varies greatly with geographic location and time of year (*see* **Cloud–Radiation Interactions**, Volume 1). Ice-albedo feedback probably leads to amplification of temperature changes in high latitudes. It arises because decreases in sea ice and snow cover, which have high albedo, decrease the radiation reflected back to space and thus produces warming that may further decrease the sea ice and snow cover extent. However, increased open water may lead to more evaporation and atmospheric water vapor, thereby increasing fog and low cloud amount, offsetting the change in surface albedo.

Other more complicated feedbacks may involve the atmosphere and ocean, e.g., cold waters off of the western coasts of continents (such as California or Peru) encourage development of extensive low stratocumulus cloud decks which block the Sun and this helps keep the ocean cold. A warming of the waters, such as during El Niño, could eliminate the cloud deck and lead to further sea surface warming because of an increase in solar radiation. El Niño itself involves strong positive and negative feedbacks that are the essence of this natural phenomenon. Warming of the oceans from increased carbon dioxide may diminish the ability of the oceans to continue to take up carbon dioxide, thereby enhancing the rate of change.

A number of feedbacks involve the biosphere and are especially important when considering details of the carbon cycle and the impacts of climate change. For example, in wetland soils rich in organic matter, such as peat, the presence of water limits oxygen access and creates anaerobic microbial decay, which releases methane into the atmosphere. If climate change acts to dry the soils, aerobic microbial activity develops and produces enhanced rates of decay, which releases large amounts of carbon dioxide into the atmosphere. Similarly, in areas of permafrost, natural gas hydrates (*see* **Methane Clathrates**, Volume 1), which are a crystalline form of water and mostly methane, can be destabilized by permafrost melting, releasing methane or carbon dioxide into the atmosphere, depending on the nature of the associated microbial activity that develops. Empirical evidence from ice cores reveals very strong parallel changes in temperatures, carbon dioxide and methane over the past 400 000 years through the major glacials and interglacials, suggesting that atmospheric concentrations of these greenhouse gases somehow responded to the climate changes underway and reinforced the changes through positive feedbacks. Much remains to be learned about these feedbacks and their possible influences on predictions of future carbon dioxide concentrations and climate.

Modeling of Climate

To quantify the response of the climate system to changes in forcing it is essential to account for all the complex interactions and feedbacks among the climate system components and this is done using numerical models of the climate system based upon well established physical principles. Global climate models include representations of all processes indicated in Figure 1. With comprehensive climate models, experiments can be run with and without increases in greenhouse gases and also other influences, such as changes in aerosols. The best models encapsulate the current understanding of the physical processes involved in the climate system, the interactions, and the performance of the system as a whole. They have been extensively tested and evaluated using observations (*see* **Model Simulations of Present and Historical Climates**, Volume 1; **Projection of Future Changes in Climate**, Volume 1). While models are exceedingly useful tools for carrying out numerical climate experiments, they are not perfect, and so have to be used carefully (Trenberth, 1997).

Attribution of Climate Change

It is desirable to examine and evaluate the past observational record by running models forced with realistic radiative forcing, although the latter is not that well known. It is in this way that models can be further tested and it may be possible to attribute the observed changes to particular changes in forcing, such as from volcanic or solar origins, and to achieve detection of the effects of human activities and specifically the effects from increases in aerosols and greenhouse gases.

Examining observed changes and comparing with the signature provide by models may enable attribution of the changes to the changes in atmospheric composition, and in 1995 the Intergovernmental Panel on Climate Change (IPCC) assessment concluded that "the balance of evidence suggests that there is a discernible human influence on global climate". Since then the evidence has become stronger (*see* **Climate Change, Detection and Attribution**, Volume 1).

For the observational temperature record (Figure 7), the best evidence compiled to date suggests that solar variability has played a small role but has contributed to some of the warming of the twentieth century – perhaps 0.2 °C – up to about 1950 (Cubasch *et al.*, 1997). Changes in aerosols in the atmosphere, both from volcanic eruptions, from increased visible pollutants and their effects on clouds have also contributed to reduced warming, perhaps by a couple of tenths of a degree C (Hansen *et al.*, 1993). Some year-to-year fluctuations may have arisen from volcanic debris, such as the temporary cooling in 1991 and 1992 following the eruption of Mount Pinatubo in June 1991 (Hansen *et al.*, 1997). Heavy industrialization following World War II may have contributed to the plateau in global temperatures from 1950–1970 or so. Natural fluctuations arising from interactions between the atmosphere and the oceans have probably also contributed to decadal fluctuations of perhaps as much as 0.1 °C in global mean temperatures, and El Niños contribute to the interannual variations, typically of one or two tenths degree C warming. It is only after the late 1970s that global warming from increases in greenhouse gases has probably emerged as a clear signal in global temperatures.

Projection of Climate Change

When a model is employed for projecting changes in climate it is first run for many simulated decades without any changes in external forcing in the system. The quality of the simulation can then be assessed by comparing the mean, the annual cycle and the variability statistics on different time scales with observations of the climate. In this way the model is evaluated (*see* **Model Simulations of Present and Historical Climates**, Volume 1). The model is then run with changes in external forcing, such as with a possible future profile of greenhouse gas concentrations. The differences between the climate statistics in the two simulations provide an estimate of the accompanying climate change. However, definitive projections of possible local climate changes, which are most needed for assessing impacts, are the most challenging to do with any certainty.

Projections have been made of future global warming effects based upon model results to the year 2100 (*see* **Projection of Future Changes in Climate**, Volume 1). Because the actions of humans are not predictable in any deterministic sense, future projections necessarily contain a "what if" emissions scenario. In addition, for a given scenario, the rate of temperature increase depends on the model and features such as how clouds are depicted, so that a range of possible outcomes exists. The IPCC projections (IPCC, 1996) for a mid-range emissions scenario in which carbon dioxide concentrations approximately double 1990 values by the year 2100 produces global mean temperature increases ranging from 1.3 to 2.9 °C above 1990 values with a best estimate of about 2 °C. However, somewhat larger temperature increases have been projected in the IPCC's Third Assessment Report (IPCC, 2001) as a result of projections that sulfur dioxide emissions are likely to be controlled. Note that while these projections include crude estimates of the effects of sulfate aerosol they deliberately omit other possible human influences such as changes in land use. A major concern is that the projected rates of climate change will exceed anything seen in nature in the past 10 000 years.

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