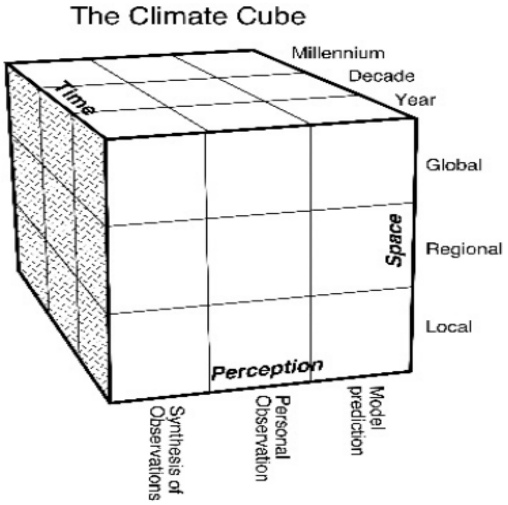
Climate Modeling

THE CLIMATE

The term 'climate' can be defined as 'all of the statistics describing the atmosphere and ocean determined over an agreed time interval (seasons, decades or longer), computed for the globe or for a selected region'. This definition is wide, but it does serve to confirm that higher-order statistics, such as variance (variability), can often be more useful in characterizing a climatic state than just the mean (average).

The definition also described the climatic change as the difference between two climatic states, and a climatic anomaly as the difference between a climatic state and the mean state. The variations of the system arise from interactions between different parts of the climate system and from external forcings. Although the greatest variations are due to changes in the phase of water (i.e. frozen, liquid or vapour), the components of the atmosphere and ocean and the characteristics of the continental surface can also change, giving rise to a need for consideration of atmospheric chemistry, ocean biogeochemistry, and land-surface exchanges.

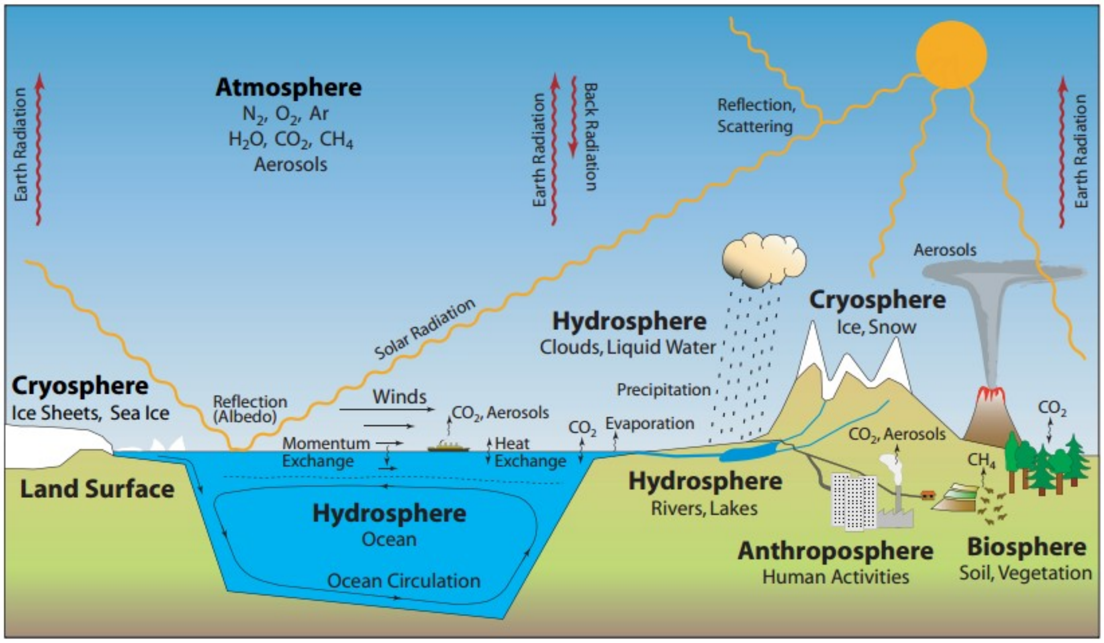
From climate cube, it can be seen that the Climate can be viewed as existing in at least three domains: time, space and human perception.



The climate system

World Meteorological Organization WMO in 1975 defined, the climate system as being composed of the atmosphere, hydrosphere, cryosphere, land surface and biosphere. In 1992, the United Nations' Framework Convention on Climate Change (FCCC) defined the climate system as 'the totality of the atmosphere, hydrosphere, biosphere and geosphere and their interactions'. These definitions are similar, but the emphasis on interactions has grown in the thirty years since 1975. The figure below shows a schematic representation of the climate system components which climate modellers must consider.

The climate system can be divided into six components which are introduced below:



1. Atmosphere

Gaseous part above the Earth's surface including traces amounts of other gaseous, liquid and solid substances. Weather, radiation balance, formation of clouds and precipitation, atmospheric flow, transport of heat, water vapour, dust and aerosols.

2. Hydrosphere

All forms of water above and below the Earth's surface. This includes the whole ocean and the global water cycle after precipitation has reached the Earth's surface. Global distribution and changes of the inflow into the different ocean basins, transport of ocean water masses, transport of heat in the ocean, exchange of water vapour and other gases between ocean and atmosphere.

3. Cryosphere

All forms of ice in the climate system, including ice masses, ice shelves, sea ice, and glaciers. Long-term water reserves, changes of the radiation balance of the Earth surface, influence on the salinity in critical regions of the ocean.

4. Land Surface

Include Solid Earth, Position of the continents, changes in sea level, transformation of short-wave to long-wave radiation, reflectivity of the Earth's surface, transfer of momentum and energy.

5. Biosphere

Organic cover of the land masses (vegetation, soil) and marine organisms. Determines the exchange of carbon between the different reservoirs, and hence the concentration of CO_2 in the atmosphere, as well as the balances of many other gases, and therefore also the radiation budget. Influences the reflectivity of the surface, hence the radiation balance.

6. Anthroposphere

consisting of the processes which are caused or altered by humans. The most important ones are the emission of substances which change the radiation balance, and land-use change (deforestation, desertification, and degradation). Most of the climate models treat processes and fluxes of the anthroposphere as an external forcing.

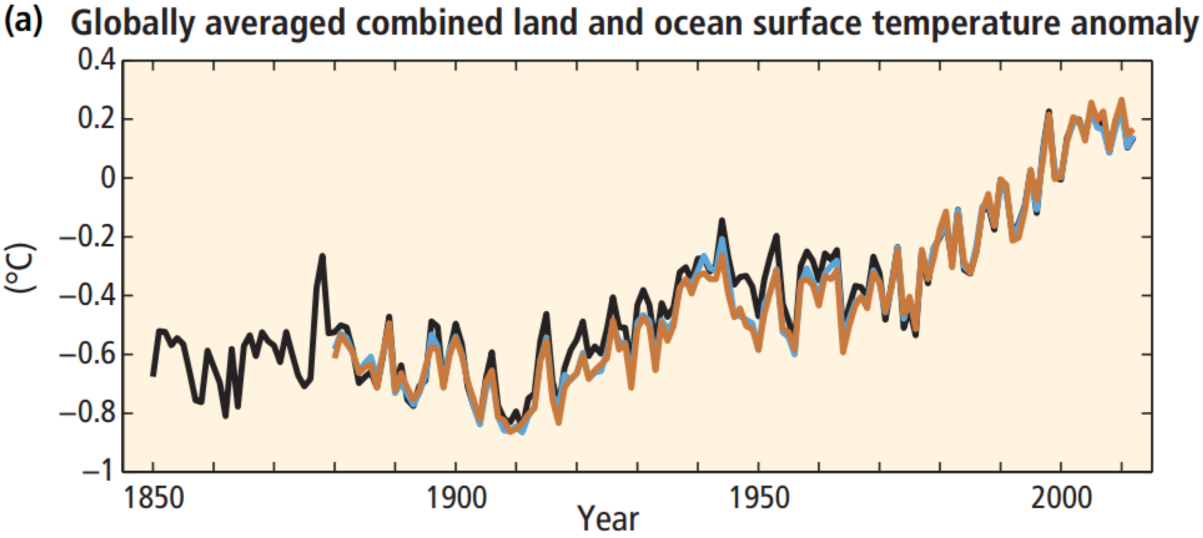
OBSERVED CHANGES AND THEIR CAUSES

Human influence on the climate system is clear, and recent emissions of greenhouse gases are the highest in history. Recent climate changes have widespread impacts on human and natural systems.

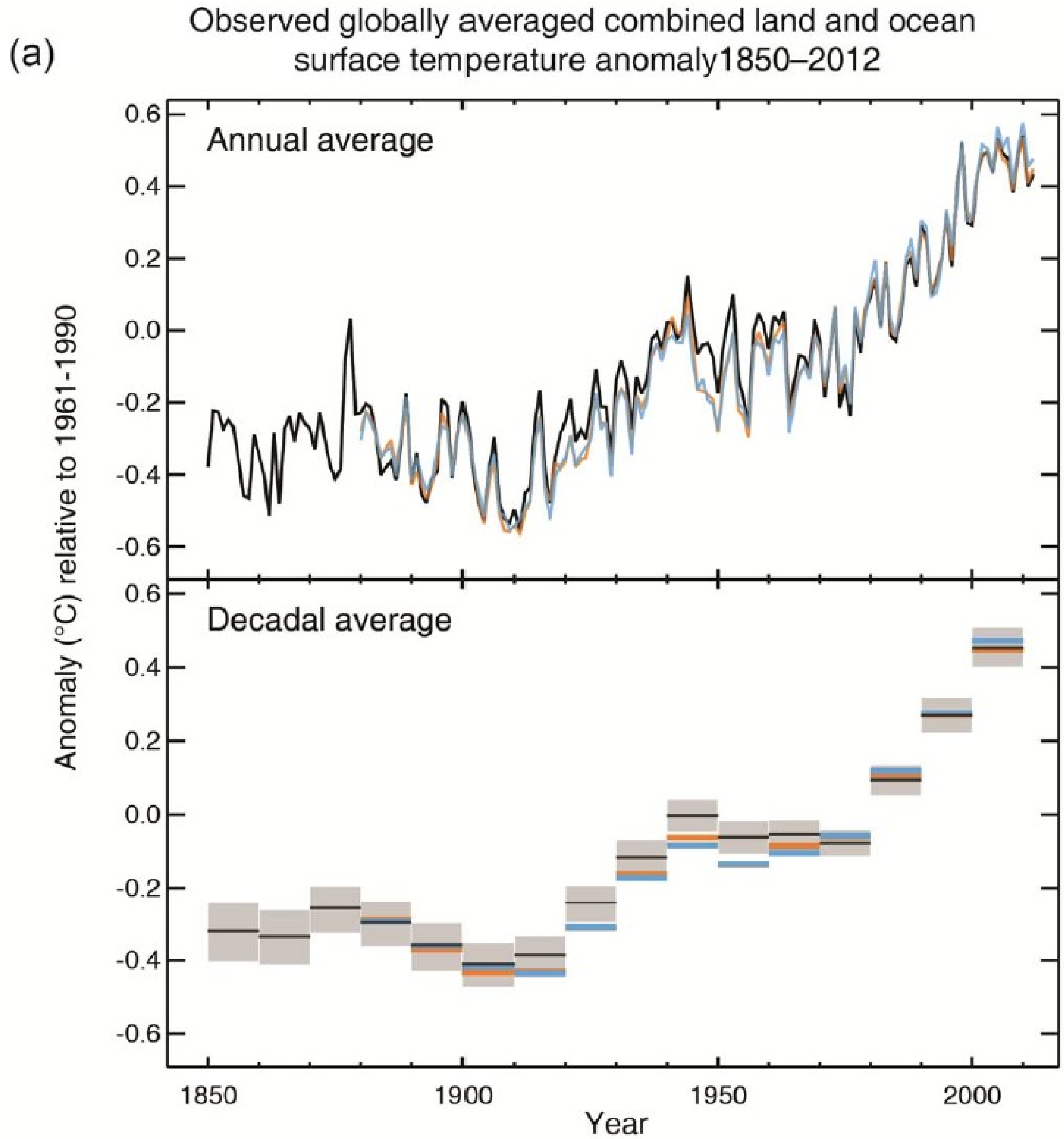
1. Observed Changes in The Climate System

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have decreased, and sea level has risen.

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. The period from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere, where such assessment is possible. The globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85 [0.65 to 1.06] °C over the period 1880 to 2012.


(a) Globally averaged combined land and ocean surface temperature anomaly

In addition to strong multi-decadal warming, the globally averaged surface temperature exhibits essential decadal and interannual variability. Due to this natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. As one example, the rate of warming over the past 15 years (1998–2012; 0.05 [–0.05 to 0.15] °C per decade), which begins with a strong El Niño, is smaller than the rate calculated since 1951 (1951–2012; 0.12 [0.08 to 0.14] °C per decade).



(a) Observed globally averaged combined land and ocean surface temperature anomaly1850–2012

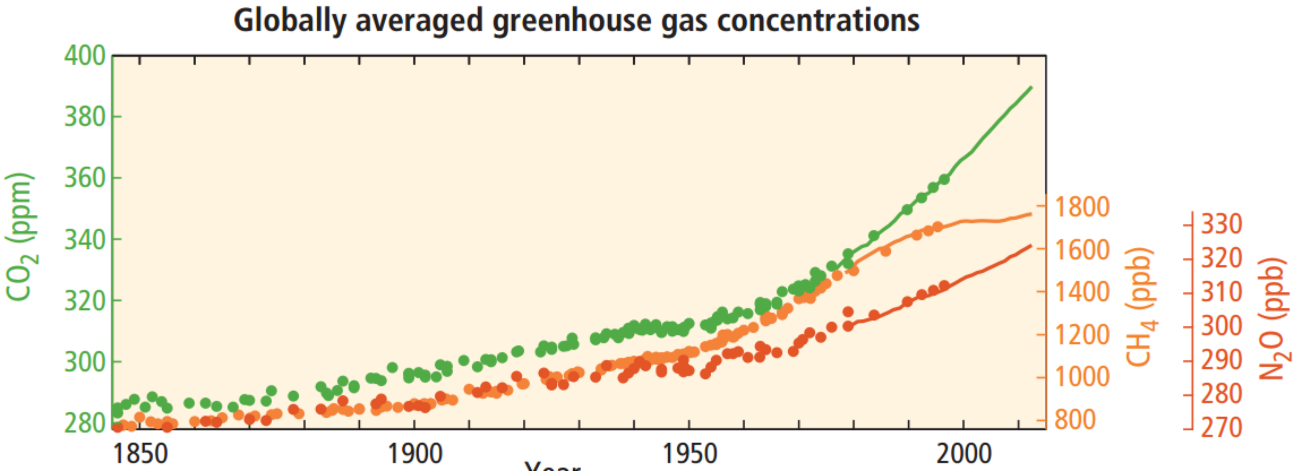
Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010, with only about 1% stored in the atmosphere. On a global scale, the ocean warming is largest near the surface, and the upper 75 m warmed by 0.11 °C per decade over the period 1971 to 2010.

Since the beginning of the industrial era, oceanic uptake of CO_2 has resulted in acidification of the ocean; the pH of ocean surface water has decreased by 0.1, corresponding to a 26% increase in acidity, measured as hydrogen ion concentration.

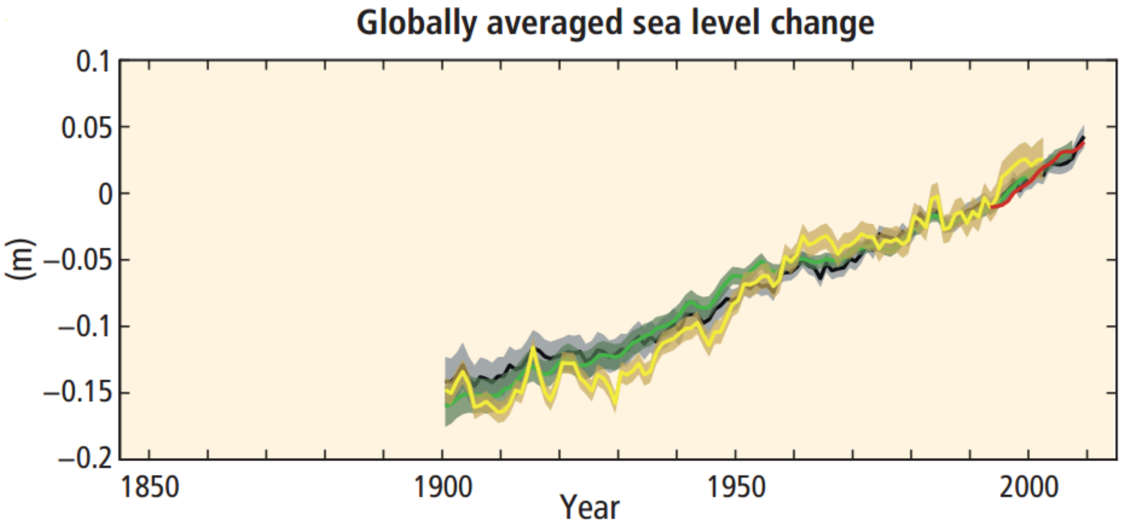
Over the period 1992 to 2011, the Greenland and Antarctic ice sheets have been losing mass, likely at a larger rate over 2002 to 2011. Glaciers have continued to shrink almost worldwide. Northern Hemisphere spring snow cover has continued to decrease in extent . There is high confidence that permafrost temperatures have increased in most regions since the early 1980s in response to increased surface temperature and changing snow cover.

The annual mean Arctic sea-ice extent decreased over the period 1979 to 2012, with a rate in the range 3.5 to 4.1% per decade. Arctic sea-ice extent has decreased in every season and decade since 1979, with the most rapid decrease in decadal mean extent in summer . It is very likely that the annual mean Antarctic sea-ice extent increased in the range of 1.2 to 1.8% per decade between 1979 and 2012.

Anthropogenic greenhouse gas (GHG) emissions since the pre-industrial era have driven large increases in the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Between 1750 and 2011, cumulative anthropogenic CO_2emissions to the atmosphere were 2040 ± 310 $GtCO_2$. About 40% of these emissions have remained in the atmosphere (880 ± 35 $GtCO_2$); the rest was removed from the atmosphere and stored on land (in plants and soils) and in the ocean. The ocean has absorbed about 30% of the emitted anthropogenic CO_2, causing ocean acidification. About half of the anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the last 40 years .



Over the period 1901 to 2010, global mean sea level rose by 0.19 [0.17 to 0.21] m . The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia.



CLIMATE FORCINGS

A climate forcing is a change imposed on the planetary energy balance that, typically, causes a change in global temperature. Forcings imposed on the climate system may be falling into two separate categories. External forcings are caused by variations in agents outside the climate system such as solar radiation fluctuations. On the other hand, internal forcing, such as volcanic eruptions, ice-sheet changes, CO_2 increases, and deforestation are variations in components of the climate system. Longer-term internal forcings occurring as a result of continental drift and mountain-building have an effect may also influence the upper atmosphere and thus, perhaps, the whole climate.

1. External causes of climatic change

Milankovitch variations

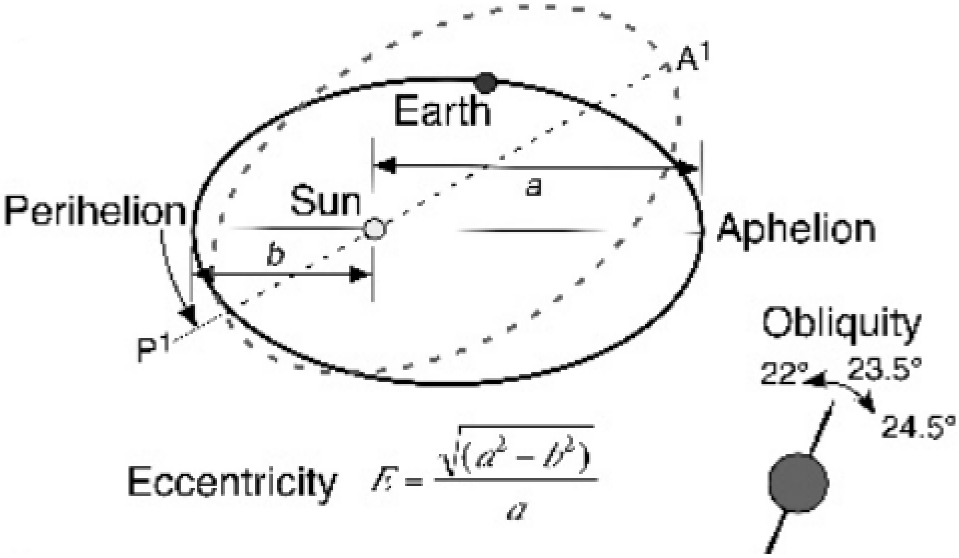
The astronomical theory of climate variations, also called the Milankovitch theory, is an attempt to relate climatic variations to the changing parameters of the Earth's orbit around the Sun. The orbit of the Earth is an ellipse around the Sun, which lies at one of the foci. There are several different ways in which the orbital configuration can affect the received radiation and thus possibly the climate :

(i) changes in eccentricity, (ii) changes in obliquity and (iii) changes in orbital precession.

The mean annual flux varies as a function of the eccentricity of the orbit, E. For a larger value of E, there is a smaller annual flux. The current value of E is 0.017. In the last 5 million years, it has varied from 0.000483 to 0.060791, resulting in changes in the incident flux of +0.014% to -0.170% from the current value (~0.19Wm^{-2} and ~2.3Wm^{-2} respectively).

The obliquity, or the tilt of the Earth's axis of rotation, is the angle between the Earth's axis and the plane of the ecliptic (the plane in which the Earth and other bodies of the solar system orbit the Sun). This tilt varies from about 22° to 24.5°, with a period of about 40000 years. The current value is 23.5°. Seasonal variations depend upon the obliquity: if the obliquity is large, so is the range of seasonality.

Due to gravitational interaction with the other planets, primarily Jupiter, the perihelion (the point of the Earth's elliptical orbit closest to the Sun) moves in space so that the ellipse is moved around in space. This orbital precession will cause a progressive change in the time of the equinoxes. These changes occur in such a way that two main periodicities are apparent: 23 000 years and 18 800 years. This change,like that of obliquity, does not alter the total radiation received but does affect its temporal and spatial distribution. For example, perihelion is currently on 5 January, in the middle of the Northern Hemisphere winter, but 11 000–15 000 years from now it will occur in July.



Solar activity

Variations in the climate during historical times have been linked with the sunspot cycle, which is a second cause of solar produced climatic change. This cycle occurs with a 22-year periodicity: the 'Hale' double sunspot cycle. The overall amplitude of the cycles seems to increase slowly and then fall rapidly with a period of 80–100 years. There also appears to be a quasi-cyclic fluctuation of the order of 180 years. Solar activity modify the radiation received by the Earth because it produces dark areas (sunspots) and bright areas (faculae) that respectively deplete and enhance emitted solar radiation.

Other external factors

Collisions of comets with the Earth and very large meteoritic impacts have been proposed as causes of climatic change, Many of the disturbances that meteoritic impacts would cause, such as an increase in stratospheric and tropospheric aerosols. It is sometimes difficult to draw a clear boundary between external and natural (i.e. not human-induced) internal forcings. The distinction really depends upon the time- and space-scales encompassed in the definition of climate.

2. Internal factors: human-induced changes

These include the emissions of greenhouse gases and aerosols, changes in land-use, and the depletion of stratospheric ozone.

Greenhouse gases

solar radiation makes the earth habitable. While 30 percent of the solar energy that reaches our world is reflected back to space, approximately 70 percent passes through the atmosphere to the earth’s surface, where it is absorbed by the land, oceans, and atmosphere, and heats the planet. This heat is then radiated back up in the form of invisible infrared light. While some of this infrared light continues on into space, the vast majority—indeed, some 90 percent gets absorbed by atmospheric gases, known as greenhouse gases, and redirected back toward the earth, causing further warming.

For most of the past 800,000 years, the concentration of greenhouse gases in our atmosphere was between about 200 and 280 parts per million. (In other words, there were 200 to 280 molecules of the gases per million molecules of air.) But in the past century, that concentration has jumped to more than 400 parts per million, driven up by human activities such as burning fossil fuels and deforestation. The higher concentrations of greenhouse gases—and carbon dioxide in particular—is causing extra heat to be trapped and global temperatures to rise.

Tropospheric aerosols and clouds

The influence of volcanic aerosols on climate has long been recognized, but the influence of tropospheric aerosols associated with industrial pollution and fossil fuel and biomass burning has only recently been identified.

Solid sulfate particles result from the oxidation of SO_2 emitted when fossil fuels are burned. Other industrial processes and natural and human-initiated biomass burning and soil erosion also contribute droplets and particulate material, both termed aerosols, to the troposphere. These aerosols are localized and have two effects on the climate system. The direct effect of aerosols is to reflect some solar radiation back into space and so act to cool the affected area, although some particulates, such as soot, are dark in color and have the opposite effect, causing local warming. The magnitude of the cooling or warming depends on the nature of the aerosols and their distribution in the atmosphere.

There is also an important indirect effect of tropospheric aerosols. They act as additional cloud condensation nuclei and cause more, smaller, drops to form in clouds, increasing the reflectivity of the clouds, further cooling the planet. The indirect effect is much harder to evaluate than the direct effect, but both are believed to lead to cooling, and there is evidence that they are of comparable magnitude.

Stratospheric ozone

The ozone destruction is due to the disturbance of the natural balance of destruction and production which existed in the stratosphere. Chlorine is the principal cause of the disturbance in ozone chemistry which produces the stratospheric polar ozone holes. Although the build-up of CFCs.

The particular reactions which act to accelerate the ozone destruction rely on the presence of free chlorine atoms and a solid surface, provided by stratospheric ice clouds. Suitable conditions exist over the Antarctic continent during the winter and to a lesser extent over the Arctic Ocean in winter. It is possible that, in addition to the role played by ice crystals in the chemistry of the ozone breakdown, volcanic aerosols may also provide a suitable surface upon which the chemistry can take place. Since CFCs, HCFCs and the hydrofluorocarbons (HFCs) that are replacing them are radiatively active, they also act to change the atmospheric temperature and this alters the rate of the chemical reactions. CFCs that remain in the troposphere are effective absorbers of infrared radiation, which would otherwise escape to space. These gases therefore act to enhance the atmospheric greenhouse and to provide a warming influence for the planet. The radiative effect of the reduced stratospheric ozone is to cool the planet. The enhanced levels of tropospheric ozone that have been observed result in a warming.

Land-surface changes

These include desertification, re- and deforestation, urbanization and major river, lake and dam engineering. Climate modellers have investigated the climatic effect of such changes on the nature of the Earth's continental surface. Desertification is a problem affecting millions of people. The sparse vegetation natural to arid and semi-arid areas can be easily removed as a result of relatively minor changes in the climate or by direct influence of human activity such as over grazing or poor agricultural practices. Removal of vegetation and exposure of bare soil increase albedo and decrease soil water storage, because of increased runoff. Less moisture available at the surface means decreased latent heat flux, leading to an increase in surface temperature. On the other hand, the increased albedo produces a net radiative loss. In climate model calculations, the latter effect appears to dominate and the radiation deficit causes large-scale subsidence.

3. Internal factors: natural changes

Volcanic eruptions

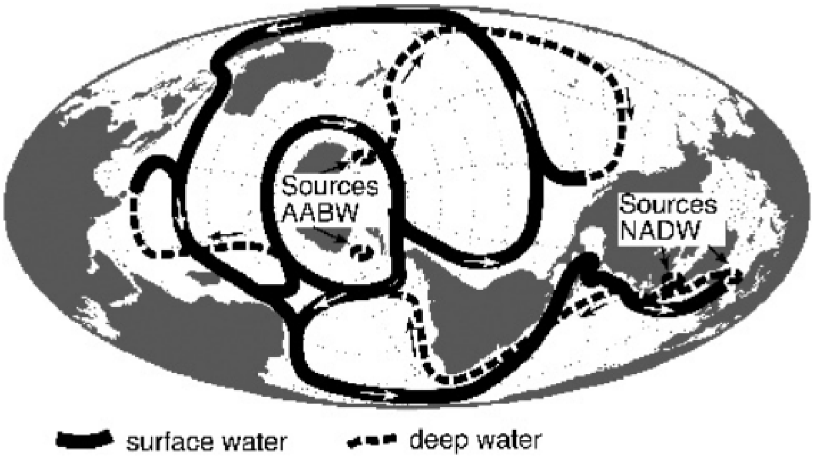
Volcanoes influence climate by projecting large quantities of particulates and gases into the atmosphere. Volcanic eruptions can thereby produce measurable tempera ture anomalies of at least a few tenths of a degree. The major climatic contribution of volcanoes is from stratospheric H_2SO_4 droplets. The effect of the injected aerosol upon the radiation balance and whether heating or cooling ensues will depend largely on the height of injection into the atmosphere. If the aerosol absorbs in the visible part of the spectrum, energy is transferred directly to the atmosphere. If the aerosol absorbs and emits in the infrared, the greenhouse effect is increased. Most eruptions inject particulates into the troposphere at heights between 5 and 8km. These are rapidly removed either by gravitational fall-out or rain-out and the resultant climatic effect is minimal. More violent eruptions hurl debris into the upper troposphere or even into the lower stratosphere (15–25km).

The aerosols have a long residence time in the stratosphere: of the order of a year for aerosols of radii 2–5 mm but as long as 12 years for smaller aerosols of radii 0.5–1.0mm. Mount Pinatubo injected around 20 million tonnes of SO_2 to heights of 25km. As it was dispersed by the stratospheric winds, the SO2 was photochemically transformed into sulphate aerosols. These non-absorbing aerosols increase the albedo of the atmosphere and reduce the amount of solar radiation that reaches the surface.

Ocean circulation changes

The ocean is one of the main constituents of the climate system. The bulk of the energy absorbed by the climate system is absorbed at the ocean surface and its huge thermal capacity and its ability to circulate this energy over long time-scales mean that its role in the climate system is powerful and complex. The circulation of the ocean combines three components: surface currents driven by the winds, deep cur rents driven by gradients of temperature and salinity, and tides driven by the gravitational effects of the Moon and Sun. These forces interact in a non-linear way to produce a complex system of motion we know as the global ocean circulation. Winds interact with regions of coastal upwelling to produce localized changes in sea-surface temperature, but perhaps the most significant changes in the ocean circulation are tied to phenomena with much longer time-scales. The circulation of the global ocean is dominated by what is termed the deep water circulation over time-scales of tens to thousands of years. There are two deep water sources active today:

the North Atlantic Deep Water (NADW) and the Antarctic Bottom Water (AABW).



The Schematic shows the thermohaline circulation of the ocean, termed the 'ocean conveyor belt'. The four main sources of deep ocean water, which lie off the Greenland and Antarctic coasts, form North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) respectively. These cold and dense waters circulate the globe first near the ocean floor and later as near-surface flows. These water masses, although both are cold and dense, have different characteristics. The slightly warmer, southward flowing NADW lies above the more dense and colder northward flowing AABW, producing the characteristic layering observed in the deep ocean. The circulation of the ocean deep water can be simplified to illustrate the principal aspects of the system. The warm surface currents flow towards regions of deep water formation, namely the Labrador and Greenland Seas in the Northern Hemisphere and the Ross and Weddell Seas in the Southern. The natural variability of the ocean circulation is an important factor for climate. The ocean circulation varies on glacial time-scales, over which the circulation is known to change markedly, and on interannual time-scales over which the El Niño Southern Oscillation (ENSO) phenomenon is important. Modellers have recently achieved some success in developing predictive models of ENSO events in the Equatorial Pacific on seasonal time-scales using spatially restricted ocean models, but the reliable prediction of El Niño events remains a challenge for the future. Over longer time-scales the ocean circulation changes markedly as changes occur in the distribution of land, either as a result of sea-level changes during periods of glaciation, or on much longer time-scales as the continents move across the Earth's surface. Another challenge which faces ocean scientists is trying to explain the sudden changes that occur in circulation patterns. For example, in the North Atlantic, the relative warmth of Europe (palms in Western Scotland) in our present era is attributable to the formation of North Atlantic Deep Water (NADW) discussed above, which maintains the flow of warm surface water from the south. However, geological evidence from mid-Atlantic ocean drilling shows that NADW production has varied greatly over the last 25000 years, seeming to be tied closely to stages of the last glaciation. Although the mechanisms that trigger changes in NADW production are not yet fully understood, computer models of the ocean circulation have been shown to support multiple equilibria for the Atlantic thermohaline circulation. This suggests that the ocean may respond abruptly to small perturbations in the hydro logical cycle.