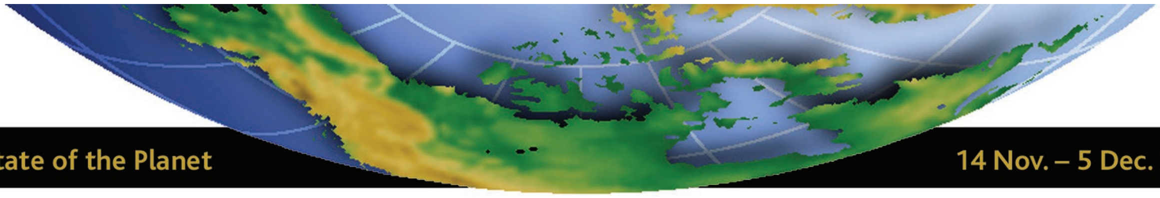

South America, because of the economic growth there, would make global air quality more of an issue in the Southern Hemisphere, a region where only biomass burning has been considered important so far.

Finally, the importance of megacities as sources of regional and global pollution is worth noting. Megacities may be defined as metropolitan areas with over 10 million inhabitants, although there is no precise accepted threshold, and population estimates are not necessarily based on the same areas of reference. In 2001, there were 17 megacities according to United Nations statistics (*47*). With rapid growth of the world's population, particularly in developing countries, and continuing industrialization and migration toward urban centers, megacities are becoming more important sources of air pollution from associated mobile and stationary sources. Air quality in megacities is thus of great concern, as illustrated by a study in Mexico City (*48*). Although the health effects of air pollution on the inhabitants of megacities are a serious social problem, its regional and global environmental consequences are also of great concern. Therefore, local, regional, and global air-quality issues, and regional and global environmental impacts, including climate change, should be viewed in an integrated manner.

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Modern Global Climate Change

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Modern climate change is dominated by human influences, which are now large enough to exceed the bounds of natural variability. The main source of global climate change is human-induced changes in atmospheric composition. These perturbations primarily result from emissions associated with energy use, but on local and regional scales, urbanization and land use changes are also important. Although there has been progress in monitoring and understanding climate change, there remain many scientific, technical, and institutional impediments to precisely planning for, adapting to, and mitigating the effects of climate change. There is still considerable uncertainty about the rates of change that can be expected, but it is clear that these changes will be increasingly manifested in important and tangible ways, such as changes in extremes of temperature and precipitation, decreases in seasonal and perennial snow and ice extent, and sea level rise. Anthropogenic climate change is now likely to continue for many centuries. We are venturing into the unknown with climate, and its associated impacts could be quite disruptive.

The atmosphere is a global commons that responds to many types of emissions into it, as well as to changes in the surface beneath it. As human balloon flights around the world illustrate, the air over a specific location is typically halfway around the world a week later, making climate change a truly global issue.

Planet Earth is habitable because of its location relative to the sun and because of the natural greenhouse effect of its atmosphere. Various atmospheric gases contribute to the greenhouse effect, whose impact in clear skies is ~60% from water vapor, ~25% from carbon dioxide, ~8% from ozone, and the rest from trace gases including methane and nitrous oxide (*1*). Clouds also have a greenhouse effect. On average, the energy from the sun received at the top of the Earth's atmosphere amounts to 175 petawatts (PW) (or 175 quadrillion watts), of which ~31% is

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reflected by clouds and from the surface. The rest (120 PW) is absorbed by the atmosphere, land, or ocean and ultimately emitted back to space as infrared radiation (*1*). Over the past century, infrequent volcanic eruptions of gasses and debris into the atmosphere have significantly perturbed these energy flows; however, the resulting cooling has lasted for only a few years (*2*). Inferred changes in total solar irradiance appear to have increased global mean temperatures by perhaps as much as 0.2°C in the first half of the 20th century, but measured changes in the past 25 years are small (*2*). Over the past 50 years, human influences have been the dominant detectable influence on climate change (*2*). The following briefly describes the human influences on climate, the resulting temperature and precipitation changes, the time scale of responses, some important processes involved, the use of climate models for assessing the past and making projections into the future, and the need for better observational and information systems.

The main way in which humans alter global climate is by interference with the natural flows of energy through changes in atmospheric composition, not by the actual generation of heat in energy usage. On a global scale, even a 1% change in the energy flows, which is the order of the estimated change to date (*2*), dominates all other direct influences humans have on climate. For example, an energy output of just one PW is equivalent to that of a million power stations of 1000-MW capacity, among the largest in the world. Total human energy use is about a factor of 9000 less than the natural flow (*3*).

Global changes in atmospheric composition occur from anthropogenic emissions of greenhouse gases, such as carbon dioxide that results from the burning of fossil fuels and methane and nitrous oxide from multiple human activities. Because these gases have long (decades to centuries) atmospheric lifetimes, the result is an accumulation in the atmosphere and a buildup in concentrations that are clearly shown both by instrumental observations of air samples since 1958 and in bubbles of air trapped in ice cores before then. Moreover, these gases are well distributed in the atmosphere across the globe, simplifying a global monitoring strategy. Carbon dioxide has increased 31% since preindustrial times, from 280 parts per million by volume (ppmv) to more than 370 ppmv today, and half of the increase has been since 1965 (*4*) (Fig. 1). The greenhouse gases trap outgoing radiation from the Earth to space, creating a warming of the planet.

Emissions into the atmosphere from fuel burning further result in gases that are oxidized to become highly reflective micron-sized aerosols, such as sulfate, and strongly absorbing aerosols, such as black carbon or soot. Aerosols are rapidly (within a week or less) removed from the atmosphere through the natural hydrological cycle and dry deposition as they travel away from their source. Nonetheless, atmospheric concentrations can substantially exceed background conditions in large areas around and downwind of the emission sources. Depending on their reflectivity and absorption properties, geometry and size distribution, and interactions with clouds and moisture, these particulates can lead to either net cooling, as for sulfate aerosols, or net heating, as for black carbon. Importantly, sulfate aerosols affect climate directly by reflecting solar radiation and indirectly by changing the reflective properties of clouds and their lifetimes. Understanding their precise impact has been hampered by our inability to measure these aerosols directly, as well as by their spatial inhomogeneity and rapid changes in time. Large-scale measurements of aerosol patterns have been inferred through emission data, special field experiments, and indirect measurements such as sun photometers (*5*).

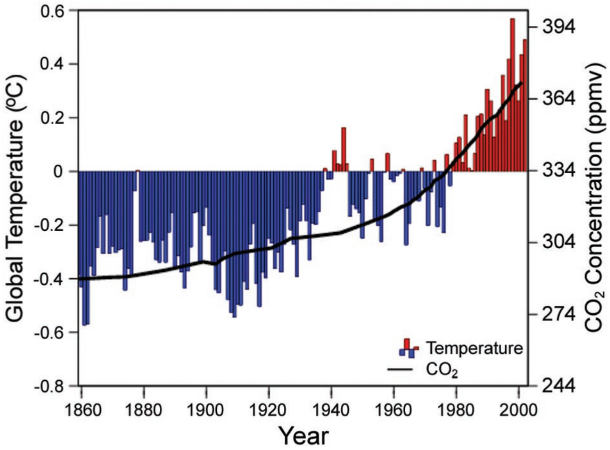


Fig. 1. Time series of departures from the 1961 to 1990 base period for an annual mean global temperature of 14.0°C (bars) and for a carbon dioxide mean of 334 ppmv (solid curve) during the base period, using data from ice cores and (after 1958) from Mauna Loa (*4*). The global average surface heating approximates that of carbon dioxide increases, because of the cancellation of aerosols and other greenhouse gas effects, but this does not apply regionally (*2*). Many other factors (such as the effects of volcanic eruptions and solar irradiance changes) are also important.

Human activities also have a large-scale impact on the land surface. Changes in land-use through urbanization and agricultural practices, although not global, are often most pronounced where people live, work, and grow food, and are part of the human impact on climate (*6*, *7*). Large-scale deforestation and desertification in Amazonia and the Sahel, respectively, are two instances where evidence suggests there is likely to be human influence on regional climate (*8*–*10*). In general, city climates differ from those in surrounding rural green areas, because of the "concrete jungle" and its effects on heat retention, runoff, and pollution, resulting in urban heat islands.

There is no doubt that the composition of the atmosphere is changing because of human activities, and today greenhouse gases are the largest human influence on global climate (*2*). Recent greenhouse gas emission trends in the United States are upward (*11*), as are global emissions trends, with increases between 0.5 and 1% per year over the past few decades (*12*). Concentrations of both reflective and nonreflective aerosols are also estimated to be increasing (*2*). Because radiative forcing from greenhouse gases dominates over the net cooling forcings from aerosols (*2*), the popular term for the human influence on global climate is "global warming," although it really means global heating, of which the observed global temperature increase is only one consequence (*13*) (Fig. 1). Already it is estimated that the Earth's climate has exceeded the bounds of natural variability (*2*), and this has been the case since about 1980.

Surface moisture, if available (as it always is over the oceans), effectively acts as the "air conditioner" of the surface, as heat used for evaporation moistens the air rather than warming it. Therefore, another consequence of global heating of the lower troposphere is accelerated land-surface drying and more atmospheric water vapor (the dominant greenhouse gas). Accelerated drying increases the incidence and severity of droughts, whereas additional atmospheric water vapor increases the risk of heavy precipitation events (*14*). Basic theory (*15*), climate model simulations (*2*), and empirical evidence (Fig. 2) all confirm that warmer climates, owing to increased water vapor, lead to more intense precipitation events even when the total precipitation remains constant, and with prospects for even stronger events when precipitation amounts increase (*16*–*18*).

There is considerable uncertainty as to exactly how anthropogenic global heating will affect the climate system, how long it will last, and how large the effects will be. Climate has varied naturally in the past, but today's circumstances are unique because of human influences on atmospheric composition. As we progress into the future, the magnitude of the present anthropogenic change will become overwhelmingly large compared to that of natural changes. In the absence of climate mitigation policies, the 90% probability interval for warming from 1990 to 2100 is 1.7° to 4.9°C (*19*). About half of this range is due to uncertainty in future emissions and about half is due to uncertainties in climate models (*2*, *19*), especially in their sensitivity to forcings that are complicated by feedbacks, discussed below, and in their rate of heat uptake by the oceans (*20*). Even with these uncertainties, the likely outcome is more frequent heat waves, droughts, extreme precipitation events, and related impacts (such as wild fires, heat stress, vegetation changes, and sea level rise) that will be regionally dependent.

The rate of human-induced climate change is projected to be much faster than most natural processes, certainly those prevailing over the past 10,000 years (*2*). Thresholds likely exist that, if crossed, could abruptly and perhaps almost irreversibly switch the climate to a different regime. Such rapid change is evident in past climates during a slow change in the Earth's orbit and tilt, such as the Younger Dryas cold event from ~11,500 to ~12,700 years ago (*2*), perhaps caused by freshwater discharges from melting ice sheets into the North Atlantic Ocean and a change in the ocean thermohaline circulation (*21*, *22*). The great ice sheets of Greenland and Antarctica may not be stable, because the extent to which cold-season heavier snowfall partially offsets increased melting as the climate warms remains uncertain. A combination of ocean temperature increases and ice sheet melting could systematically inundate the world's coasts by raising sea level for centuries.

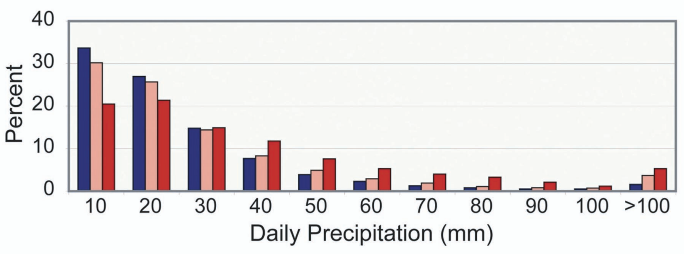


Fig. 2. Climatology of the intensity of daily precipitation as a percentage of total amount in 10 mm/day categories for different temperature regimes, based on 51, 37, and 12 worldwide stations, respectively: blue bars, –3°C to 19°C; pink bars, 19°C to 29°C; dark red bars, 29°C to 35°C. By selection, all stations have the same seasonal mean precipitation amount of 230 ± 5 mm. As temperatures and the associated water-holding capacity of the atmosphere (*15*) increase, more precipitation falls in heavy (more than 40 mm/day) to extreme (more than 100 mm/day) daily amounts.

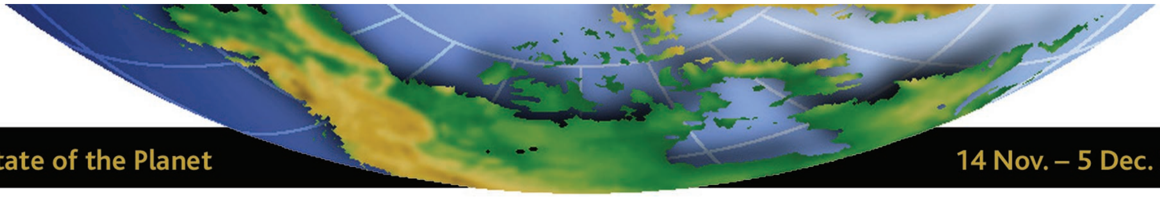
Given what has happened to date and is projected in the future (*2*), substantial further climate change is guaranteed. The rate of change can be slowed, but it is unlikely to be stopped in the 21st century (*23*). Because concentrations of long-lived greenhouse gases are dominated by accumulated past emissions, it takes many decades for any change in emissions to have much effect. This means the atmosphere still has unrealized warming (estimated to be at least another 0.5°C) and that sea level rise may continue for centuries after an abatement of anthropogenic greenhouse gas emissions and the stabilization of greenhouse gas concentrations in the atmosphere.

Our understanding of the climate system is complicated by feedbacks that either amplify or damp perturbations, the most important of which involve water in various phases. As temperatures increase, the water-holding capacity of the atmosphere increases along with water vapor amounts, producing water vapor feedback. As water vapor is a strong greenhouse gas, this diminishes the loss of energy through infrared radiation to space. Currently, water vapor feedback is estimated to contribute a radiative effect from one to two times the size of the direct effect of increases in anthropogenic greenhouse gases (*24*, *25*). Precipitation-runoff feedbacks occur because more intense rains run off at the expense of soil moisture, and warming promotes rain rather than snow. These changes in turn alter the partitioning of solar radiation into sensible versus latent heating (*14*). Heat storage feedbacks include the rate at which the oceans take up heat and the currents redistribute and release it back into the atmosphere at variable later times and different locations.

Cloud feedback occurs because clouds both reflect solar radiation, causing cooling, and trap outgoing long-wave radiation, causing warming. Depending on the height, location, and the type of clouds with their related optical properties, changes in cloud amount can cause either warming or cooling. Future changes in clouds are the single biggest source of uncertainty in climate predictions. They contribute to an uncertainty in the sensitivity of models to changes in greenhouse gases, ranging from a small negative feedback, thereby slightly reducing the direct radiative effects of increases in greenhouse gases, to a doubling of the direct radiative effect of increases in greenhouse gases (*25*). Clouds and precipitation processes cannot be resolved in climate models and have to be parametrically represented (parameterized) in terms of variables that are resolved. This will continue for some time into the future, even with projected increases in computational capability (*26*).

Ice-albedo feedback occurs as increased warming diminishes snow and ice cover, making the planet darker and more receptive to absorbing incoming solar radiation, causing warming, which further melts snow and ice. This effect is greatest at high latitudes. Decreased snow cover extent has significantly contributed to the earlier onset of spring in the past few decades over northern-hemisphere high latitudes (*27*). Ice-albedo feedback is affected by changes in clouds, thus complicating the net feedback effect.

The primary tools for predicting future climate are global climate models, which are fully coupled, mathematical, computer-based models of the physics, chemistry, and biology of the atmosphere, land surface, oceans, and cryosphere and their interactions with each other and with the sun and other influences (such as volcanic eruptions). Outstanding issues in modeling include specifying forcings of the climate system; properly dealing with complex feedback processes (Fig. 3) that affect carbon, energy, and water sources, sinks and transports; and improving simulations of regional weather, especially extreme events. Today's inadequate or incomplete measurements of various forcings, with the exception of well-mixed greenhouse gases, add uncertainty when trying to simulate past and present climate. Confidence in our ability to predict future climate is dependent on our ability to use climate models to attribute past and present climate change to specific forcings. Through clever use of paleoclimate data, our ability to reconstruct past forcings should improve, but it is unlikely to provide the regional detail neces-



sary that comes from long-term direct measurements. An example of forcing uncertainty comes from recent satellite observations and data analyses of 20th-century surface, upper air, and ocean temperatures, which indicate that estimates of the indirect effects of sulfate aerosols on clouds may be high, perhaps by as much as a factor of two (*27–29*). Human behavior, technological change, and the rate of population growth also affect future emissions and our ability to predict these must be factored into any long-term climate projection.

Regional predictions are needed for improving assessments of vulnerability to and impacts of change. The coupled atmosphere-ocean system has a preferred mode of behavior known as El Niño, and similarly the atmosphere is known to have preferred patterns of behavior, such as the North Atlantic Oscillation (NAO). So how will El Niño and the NAO change as the climate changes? There is evidence that the NAO, which affects the severity of winter temperatures and precipitation in Europe and eastern North America, and El Niño, which has large regional effects around the world, are behaving in unusual ways that appear to be linked to global heating (*2*, *31–33*). Hence, it is necessary to be able to predict the statistics of the NAO and El Niño to make reliable regional climate projections.

Ensembles of model predictions have to be run to generate probabilities and address the chaotic aspects of weather and climate. This can be addressed in principle with adequate computing power, a challenge in itself. However, improving models to a point where they are more reliable and have sufficient resolution to be properly able to represent known important processes also requires the right observations, understanding, and insights (brain power). Global climate models will need to better integrate the biological, chemical, and physical components of the Earth system (Fig. 3). Even more challenging is the seamless flow of data and information among observing systems, Earth system models, socioeconomic models, and models that address managed and unmanaged ecosystems. Progress here is dependent on overcoming not only scientific and technical issues but also major institutional and international obstacles related to the free flow of climate-related data and information.

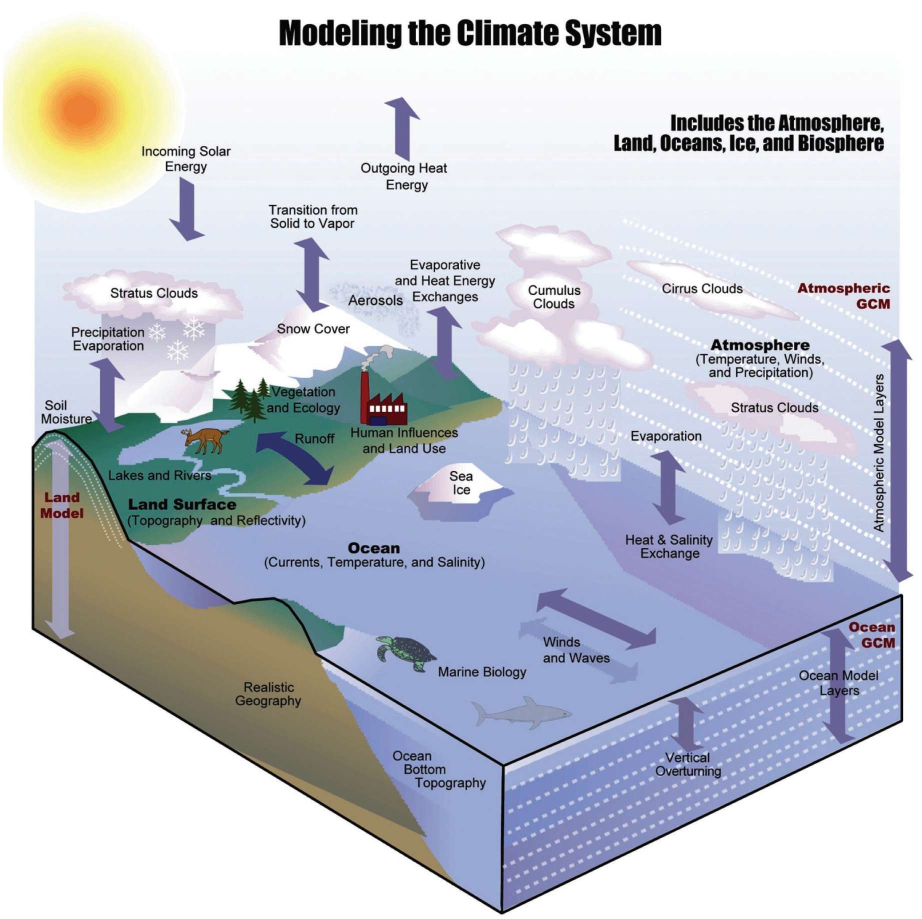


Fig. 3. Components of the climate system and the interactions among them, including the human component. All these components have to be modeled as a coupled system that includes the oceans, atmosphere, land, cryosphere, and biosphere. GCM, General Circulation Model.

In large part, reduction in uncertainty about future climate change will be driven by studies of climate change assessment and attribution. Along with climate model simulations of past climates, this requires comprehensive and long-term climate-related data sets and observing systems that deliver data free of time-dependent biases. These observations would ensure that model simulations are evaluated on the basis of actual changes in the climate system and not on artifacts of changes in observing system technology or analysis methods (*34*). The recent controversy regarding the effects that changes in observing systems have had on the rate of surface versus tropospheric warming (*35*, *36*) highlights this issue. Global monitoring through space-based and surface-based systems is an international matter, much like global climate change. There are encouraging signs, such as the adoption in 1999 of a set of climate monitoring principles (*37*), but these principles are impotent without implementation. International implementation of these principles is spotty at best (*38*).

We are entering the unknown with our climate. We need a global climate observing system, but only parts of it exist. We must not only take the vital signs of the planet but also assess why they are fluctuating and changing. Consequently, the system must embrace comprehensive analysis and assessment as integral components on an ongoing basis, as well as innovative research to better interpret results and improve our diagnostic capabilities. Projections into the future are part of such activity, and all aspects of an Earth information system feed into planning for the future, whether by planned adaptation or mitigation. Climate change is truly a global issue, one that may prove to be humanity's greatest challenge. It is very unlikely to be adequately addressed without greatly improved international cooperation and action.

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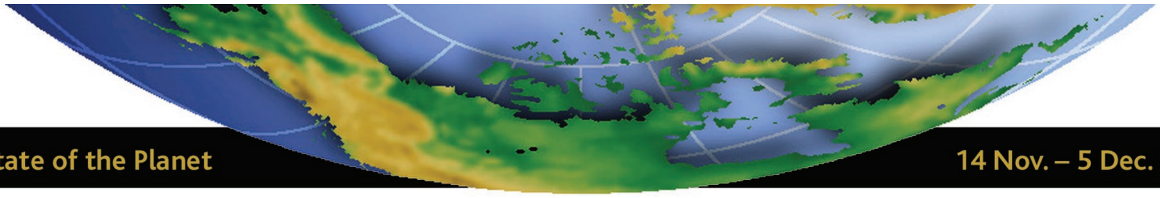

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Web Resources

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