Global Climate Change

The factors and processes involved in climate change are many and complex, ranging from fluctuations in the Earth's orbit to changes in biota. The Earth's climate has always been in flux, but indications are that human impacts from industrialization, land-use change, and growing population are speeding a warming of the planet that could have substantial effects on ecosystems and the services they provide.

Global climate change refers to alteration in climate (temperature, precipitation, and wind patterns) over a significant area lasting for an extended period. The complex set of processes involved in climate change includes impacts from land use (ice coverage and vegetation shifts, deforestation, development, urbanization, infrastructure deployment), natural and human-induced forcing factors, and feedback processes within the climate and Earth systems. It has long been recognized that the Earth's climate is in constant flux and that human activity can induce change, but the apparent complexity and underlying drivers of climate change have only come to light during the past century aided by technological advances and accumulated evidence. Population and economic growth are the major anthropogenic (human-generated) drivers of change in natural resources, land use, and their climate feedback processes. This discussion addresses forcing factors for global climate change and associated feedback mechanisms.

Climate

Climate is primarily regulated by the amount of energy absorbed and dissipated by the Earth's surface. Incoming shortwave radiation emitted by the sun passes through the atmosphere and strikes the Earth's surface. There it is either absorbed or is reflected as longwave radiation, depending on the albedo (the reflective property of the surface, including cloud cover) at that location. Some of the reflected radiation is trapped by greenhouse gases in the atmosphere (e.g., carbon dioxide [CO_2], methane [CH_4], nitrogen oxides [NOx], and water vapor), resulting in what is known as the greenhouse effect. This effect is largely responsible for Earth's average surface temperature of approximately 15°C, to which we have grown accustomed; removal of greenhouse gases would reduce the average surface temperature to about −18°C.

The amount of energy Earth receives from the sun varies with latitude. The sun's rays hit the equator directly, causing tropical regions to receive a large amount of energy. At higher latitudes, the same incoming solar radiation is distributed over a larger surface area of the Earth, creating the temperate and polar zones. The uneven distribution of heat across land and oceans fuels atmospheric circulation (Hadley circulation), thereby creating climate and precipitation patterns across the planet. This translates into weather patterns that develop in the lower atmosphere and are driven by incoming heat from the sun, the Earth's rotation, and heat stored in oceans and the atmosphere. The storage capacity of heat in the atmosphere is a function of the relative amount of the incoming radiation that can be absorbed by the different greenhouse gases in the atmosphere. Large water masses (oceans) have a high capacity to store heat and therefore cool and warm very slowly.

The temperature differences between land, oceans, and air ultimately drive climate and explain temperature and precipitation patterns along the Earth's surface in a predictable fashion. As a consequence of this predictability, biota adapts to geographical locations of the Earth in highly recognizable forms such as tropical, temperate, arid, or polar biomes. In turn, these biological systems can also affect climate as they exchange large amounts of greenhouse gases with the atmosphere, particularly CO_2 and water vapor. Therefore, any factors that impact the biosphere–atmosphere energy balance may result in relatively rapid climate change.

Recent Change

Satellite, weather balloon, and ground observations all agree that there has been a steady warming trend in the Earth's surface temperatures and that it has been more apparent over the course of the nineteenth and twentieth centuries. Based on meteorological data, the twentieth century can be divided into three sections: early twentieth-century warming, a mid-century cooling episode, and late twentieth-century warming (Anderson, Goudie, and Parker 2007).

Descriptions of early twentieth-century warming documented the changing time periods marked by the occurrence and intensity of first and last snowfalls or ice covers: for example, they noted how the snow period declined from 150 days to 113 days in London, or when the period of time during which ice cover in the Arctic Sea prevented navigation shortened from 12–13 weeks to 3–4 weeks per year, or when polar ice thickness declined 20–40 percent depending on location. During the early twentieth century sea temperature records reveal about a 1°C–2°C increase until the 1960s in northern latitudes. These increases in temperature were corroborated by independent biological observations, including the northward expansion of cod, halibut, or haddock in Greenland, displacement of fish by warm-adapted species in the southern limits (though overfishing has contributed somewhat to these effects), and the northward range shifts of plant species and birds, including the invasion of tundra by trees between 1920 and 1940. This warming period also impacted agricultural and silvicultural practices, as the number of growing days increased, and cultivation of rye, barley, or oats expanded into high latitudes in Scandinavia (expansion not caused by breeding) (Anderson, Goudie, and Parker 2007).

The mid-century cooling period occurred between about 1945 and 1970 on land and 1955 and 1975 in the oceans. Unlike the early twentieth-century period, when 85 percent of the Earth's surface experienced warming, during the mid-century cooling period 80 percent of the total Earth surface area experienced cooling. During this period glaciers stopped retreating, snowbanks were formed in the Canadian Arctic, snowfall increased in Europe, Baltic Sea ice increased, and the plant-growing season was documented to be shortened in parts of northern Europe.

The late twentieth-century warming period is characterized by a rapid increase in temperatures over continents at mid latitudes (40–70 degrees north). Temperatures rose 0.6°C in about two decades, the fastest and largest increase in temperature known over the last thousand years. This warming trend has primarily affected night-time temperatures as increased cloud cover has contributed to reduced diurnal temperature oscillations. During this current period similar climatic and biological trends that characterized the early twentieth-century warming period have been observed. Glacier retreat and melting of the permafrost (at about 4–5 kilometers a year) have been particularly well documented. Also, the onset of spring for both plant and animal life is occurring five to eleven days earlier than indicated in the historical record.

In addition to increases in temperature during the twentieth century, global precipitation has increased by about 2 percent in response to the higher evaporation rates of ocean waters. The magnitude of rainfall events has increased in many areas of the Northern Hemisphere and Australia. The increase in precipitation at northern latitudes is contrasted with decreased precipitation and increased aridity at low latitudes, particularly in northern Africa and Asia, indicating that climate shifts will not be uniform. Much of the variability observed in precipitation patterns is also related to the El Niño Southern Oscillation (ENSO), the complex of warm ocean current and associated atmosphere that influences continental climate in many regions of the world.

Multiple lines of evidence indicate changes in climate over the last 150 years. Debate continues, however, on what is causing the temperature and precipitation changes since the late nineteenth century. Changes in atmospheric chemistry due to human activities that can lead to both warming (greenhouse gases) and cooling (aerosols) seem to explain a large part of the surface temperature oscillations at short-term scales.

Natural Drivers

The Earth's climate has continuously changed during the planet's history. In the past, climate was largely impacted by natural physical, chemical, and biological processes and the feedback between these. Tectonics, which creates land and moves continents on the Earth's surface, clearly influences climate, but because continental movement is very slow, tectonics alter climate over tens of millions of years. Over the last 2–3 million years climate has changed more rapidly, with spans of tens of thousands of years forming cold (glacial) periods and warm (interglacial) periods. These climate changes can largely be explained by planetary forcing agents that affect the amount of incoming energy from the sun hitting the Earth's surface. The theory of orbital forcing developed by the Scottish scientist James Croll in the 1860s and advanced by the Serbian civil engineer and mathematician Milutin Milankovitch in the 1920s describes how the eccentricity, axial tilt, and precession of the Earth's orbit in relation to the sun drive glacial–interglacial variations (Imbrie and Imbrie 1979). Slight variations in these parameters directly impact the amount of solar radiation reaching the Earth and subsequently impact the seasonality and location of solar energy.

The Earth and all other planets in our solar system orbit the sun in an elliptical manner. The eccentricity of the orbit, or the departure of the ellipse from circularity, is determined by the interactions between the gravitational fields of Jupiter and Saturn. The ellipticity of Earth's orbit varies from 0 to 5 percent on a cycle of roughly 100,000 years. Variations in eccentricity account for how far the Earth is from the sun and have contributed to historic glacial regimes. The angle of Earth's axial tilt in relation to its plane of orbit around the sun is responsible for seasonal variation in daylight and temperature. Currently the axial tilt of the Earth is close to 23.5 degrees and decreasing; Earth's tilt naturally varies from approximately 21.4 degrees to 24.5 degrees on a roughly 41,000-year cycle. Additionally, the Earth's precession governs how the Earth wobbles as it spins on its axis and operates on a periodicity of about 23,000 years, further modulating seasonality. Evidence from deep-sea sediments and ice cores suggest considerable climate variability is associated with orbital forcing (Imbrie et al. 1992).

Regarding shorter time scales, it has been hypothesized that shifts in the quality (via changes in ultraviolet [UV] range) and quantity (via sunspots) of solar radiation at the Earth's surface can also result in changes in climate (Lean 2010). Research suggests that the number of sunspots varies on a roughly eleven-year cycle and can alter solar output by approximately 0.01 percent. During periods of high sunspot activity, the Earth receives increased radiation compared to periods with low activity. It is thought that since 1750 increased solar irradiance has been responsible for a positive radiative forcing of 0.06 to 0.30 watts per square meter (W/m^2) (IPCC 2007). This is sufficient to contribute to moderate increases in temperature in the upper atmosphere but cannot account for most of the observed increases in surface temperatures.

Volcanic eruptions may also play an important role in the Earth's climate through two primary pathways: first through the emissions of CO_2 and other greenhouse gases into the atmosphere and second by emissions of aerosols (suspensions of fine particles in gas) such as ash and sulfur gases. Water vapor and CO_2 are the primary greenhouse gases emitted and represent between 50–90 percent and 1–40 percent of annual volcanic emissions, respectively. The water vapor dissipates from the atmosphere rapidly, resulting in a negligible effect on climate, while the magnitude of CO_2 from volcanic origins is less than 1 percent of annual CO_2 emissions (Gerlach 1991). Additionally, ash and sulfur gases are projected into the stratosphere and can contribute to global cooling. These aerosols reflect incoming radiation back to space, leading to cooling of ground surface temperature. Volcanic ash is usually removed rapidly (within one month after the eruption) from the atmosphere by sedimentation (Pinto, Turco, and Toon 1989). Sulfur gases from volcanic activity represent about 36 percent of the annual tropospheric sulfur emissions (Graf, Feichter, and Langmann 1997) and are largely responsible for the climatic effects associated with eruptions because of their longer residence times in the atmosphere and their role of scattering solar radiation back to space.

Additionally, natural fluctuations in Earth's albedo resulting from shifts in land or cloud cover can impact climate patterns by altering the amount of solar radiation that is reflected or is absorbed by the Earth's surface. For instance, increased snow cover can increase reflectance and thereby alter the Earth's albedo, resulting in further cooling. In contrast, increased vegetation can result in what is called vegetative forcing, which lowers the land surface albedo and results in increased absorption of heat, thereby raising surface temperatures.

As previously mentioned, the Earth's atmospheric and oceanic conditions are closely coupled, and thus alterations in patterns of oceanic circulation can have considerable impact on global climate. The combined effects of heating/cooling and salinity drive the oceanic currents to circulate water throughout the Earth's oceans. This is known as thermohaline circulation and is responsible, for instance, for warming the North Atlantic regions by as much as 5°C. Evidence suggests that thermohaline circulation has been disrupted a number of times in the past, resulting in considerable alterations of regional temperatures. For example, evidence suggests the Younger Dryas, a millennium-long cold period about twelve thousand years ago, at the beginning of the Holocene, may have been triggered by the release of freshwater into the North Atlantic, altering ocean circulation (Broecker 1997). A shift in the ocean's thermohaline circulation could occur with increased precipitation at higher latitudes, which would reduce salinity and thereby disrupt circulation (Stocker and Schmittner 1997).

Anthropogenic Drivers

Humans, like most organisms, modify their environmental surroundings. As such, it is logical that the magnitude of modification by humans has grown in conjunction with population. The rapid growth of the human population has been fueled by the consumption of natural resources. Extraction of these natural resources is both energy and land intensive. Recently an increasing body of scientific literature suggests that there is compelling evidence that human activities are modifying forcing factors that influence climate (IPCC 2007). These human impacts are due in large part to the increased emission of greenhouse gases through the burning of fossil fuels (such as coal and petroleum), industrial activity, land-use change, and deforestation practices, all of which became prevalent during the industrial development of the past 250 years.

Human activities in large part bear responsibility for the increases in atmospheric greenhouse gases, which alter the Earth's energy budget through a process known as radiative forcing. Increased concentrations of these gases in the atmosphere contribute to global warming by absorbing energy reflected from Earth and re-emitting this energy, resulting in a net increase of energy. Humans have increased atmospheric CO_2 concentrations through fossil fuel combustion (estimated at 7.2 gigatons of carbon [GtC] per year from 2000 to 2005) and to a lesser extent by land clearing (estimated at 1.6 GtC per year during the 1990s) (IPCC 2007). These emissions have increased global CO_2 concentrations from preindustrial-era levels of about 280 parts per million (ppm) to about 389 ppm in 2011, far exceeding the range (180 to 300 ppm) from the last 420,000 years as determined from ice cores (Petit et al. 1999; IPCC 2007). Evidence suggests the increased atmospheric CO_2 has contributed to the global temperature increase from 1850/1899 to 2005 of an average 0.76°C (range of 0.57°C–0.95°C) (IPCC 2007). These patterns are particularly concerning due to the fact that CO_2 has a one-hundred- to two-hundred-year residency in the atmosphere, resulting in potentially long-lasting consequences. Three lines of evidence show that CO_2 increases are anthropogenic (Prentice et al. 2001). First, atmospheric oxygen is declining in line with CO_2 combustion. Second, the isotopic signature of fossil fuel (lack of carbon 14 [^{14}C] and depleted carbon 13 [^{13}C]) is detected in atmospheric measurements. Finally the increase in CO_2 is more rapid in the Northern Hemisphere where the majority of fossil fuels are combusted.

Humans have also contributed to the increase in a variety of other trace gases (principally methane, nitrous oxide, and halocarbons) that may have radiative forcing effects that are comparable to and higher than that of CO_2. Humans are now responsible for nearly 70 percent of annual methane atmospheric accumulation as a result of agricultural practices (i.e., livestock farming and rice cultivation), fossil fuel combustion, and decomposition associated with landfills. This has led to an increase in global methane concentrations from about 320–715 parts per billion (ppb) during the preindustrial period to 1,774 ppb in 2005 (IPCC 2007). Although methane has a relatively short residence time in the atmosphere (about twelve years) compared to CO_2, it exhibits 3.7 times more global warming potential per mole (Lashof and Ahuja 1990). Nitrous oxides have also increased from preindustrial levels of about 270 ppb to 319 ppb in 2005, primarily due to the burning of fuels at high temperatures such as in factories and cars (IPCC 2007). Finally, concentrations of halocarbons have increased significantly due to their use in synthetic organic compounds. The combined impacts of these trace gases have been estimated between 0.88 and 1.08 W/m^2, which constitutes nearly 60 percent of the radiative forcing of CO_2 (IPCC 2007).

Unlike CO_2 and other greenhouse gases that warm the atmosphere via positive radiative forcing, aerosols cool the atmosphere by reflecting incoming radiation (as in the case of large volcanic eruptions). Aerosols can contain a broad collection of particles with different chemical properties causing each to interact uniquely with the atmosphere. They can attract water and serve as cloud condensation nuclei, resulting in more diffuse clouds, which reflect more solar radiation. Sulfur dioxide produced from fossil fuel combustion and the burning of vegetation is the primary atmospheric aerosol. Aerosols are not long-lived in the atmosphere and are generally localized to the region of production. Although anthropogenic aerosol emissions have declined in North America and Europe due to more stringent regulations, emissions have increased in Asia as urbanization has increased.

Human population growth has relied on the widespread transformation of the Earth's surface to provide necessary resources, and current consensus suggests that humans have transformed or degraded somewhere between 39 and 50 percent of the Earth's surface (Vitousek et al. 1986 and 1997). Land surface change through deforestation, reforestation, and urbanization alters the albedo of the Earth's surface, impacting the amount of energy absorbed. Estimates indicate that the impacts of land transformation on Earth's albedo accounts for a loss of 0.4 W/m^2 (IPCC 2007), and therefore affecting the energy balance of the Earth's surface.

Feedback Mechanisms

To further complicate the variable climate system on Earth, global conditions are also modified by natural and human-induced feedback mechanisms, which operate on complex spatial and temporal scales. Climate feedback can be either positive or negative: positive feedback processes magnify an effect, causing increased warming or cooling, while negative feedback processes dampen change in climate.

An important feedback mechanism impacting climate is the flux of CO_2 into and from oceans; when global temperatures become warmer, CO_2 may be released from oceans. Increasing CO_2 concentrations may amplify warming by enhancing the greenhouse effect. When temperatures become cooler, CO_2 enters the ocean and contributes to additional cooling. During the last 650,000 years, CO_2 levels have tended to track glacial cycles: during warm interglacial periods, CO_2 levels have been high, and during cool glacial periods, CO_2 levels have been low.

Another important positive feedback process is the natural emission of CO_2 from soils (soil respiration), specifically in boreal ecosystems. As boreal ecosystems experience warming, they will release the large stocks of carbon that are currently immobilized (sequestered) in soils by frost, leading to further increases of CO_2 in the atmosphere. Furthermore, soil respiration has been shown to be correlated with temperature and moisture, such that increases in soil temperature in conjunction with moisture may result in increased natural CO_2 emissions rates from ecosystems (Wildung, Garland, and Buschbom 1975).

Alterations to the Earth's surface can also result in complex feedback effects on climate. Ice-albedo feedback refers to the lower albedo that snow and ice have compared to ground and vegetation, resulting in increased reflectance of energy into space. Periods of low temperatures allow snow cover to last for a longer duration, causing increased reflectance and the cooling of Earth's climate, which in turn can result in further expansion of ice cover (positive feedback). This process can also work in reverse, whereby reduced ice coverage creates feedback in which the Earth's surface warms, resulting in glacial recession. Current scientific consensus indicates that glaciers and ice caps have been losing mass, particularly since the early 1960s (Kaser et al. 2006).

Water vapor feedback in conjunction with other processes can amplify climate change. Despite its short residence time in the atmosphere, water vapor is a potent greenhouse gas. It has a heat-amplifying effect and tends to increase in conjunction with temperature, thus creating positive feedback. But water vapor also forms clouds that block incoming radiation, resulting in the cloud negative feedback effect (Ramanthan et al. 1989). A negative feedback effect by clouds is thought to be partly responsible for the observed moderate increases in surface temperature, which are less than expected given the accumulation of greenhouse gases in the atmosphere.

A study investigating feedback between climate and boreal forest vegetation cover during the Holocene epoch highlights the significance of orbital forcing, vegetation shifts, and feedback between these two parameters (Foley et al. 1994). The study suggests that orbital forcing (i.e., shifts in Earth's eccentricity, tilt, and precession), while capable of increasing global temperatures by 2°C during the mid Holocene, was not solely responsible for the observed warmer temperatures during the period. Instead, orbital forcing paired with its positive feedback effect on the northward expansion of boreal forests in high latitudes was likely to have contributed to the warmer temperatures observed. While not all feedback mechanisms are understood, research indicates that they are important in determining Earth's climate.

Sustainability, Biodiversity, and Resource Management

It is likely that human impacts on the global climate will continue, as global population and per capita energy consumption continue to rise. These impacts may be beyond the capacity for many ecosystems to adapt naturally, leading to losses of biodiversity and impacting ecosystem function and services. Consequently, climate change will be a major driver of decision making in natural resource management.

Global climate change can impact ecosystems and associated organisms in many ways. For instance, plants and animals may shift their ranges dramatically, moving as much as 6.1 kilometers per year toward the poles (Parmesan and Yohe 2003). The ability of individual species to respond to climate change will, however, likely be impeded by human-induced land habitat fragmentation, which breaks down ecosystem connectivity and produces isolated islands of habitats (Honnay et al. 2002). An additional change may be in timing, specifically in the advancement of spring events in temperate ecosystems, which is occurring 2.3 days earlier per decade (Parmesan and Yohe 2003). In coastal areas, ecosystems and urban systems will need to adapt to increases in sea level. These changes may not occur uniformly across the globe, however, but may occur faster in coastal areas or near the poles where temperature changes are more rapid.

As species shift in range, timing, and composition, ecosystem function will also change. The potential degradation of ecosystem function will threaten the ecosystem services provided to human society by nature, resulting in increased economic costs for these services. The impacts of global change on humanity will be contingent on society's ability to adapt to this change. Such an adaptation may necessitate coordinated ecosystem management across geopolitical boundaries to minimize the global impacts of climate change—a significant challenge considering the uncertainties regarding the rate and magnitude of change that has created difficulty in garnering international support to curb climate change.

A proposed adaptation technique is active ecosystem management. For instance, humans can mediate natural CO_2 storage by speeding up the rate of sequestration and reducing the release of already stored carbon. This may be accomplished through reforestation efforts or by increasing the growth rate of forests and practicing no-till agriculture. Additionally, deepwater or geologic sequestration of CO_2 may provide an alternative means to reduce atmospheric greenhouse gas concentrations.

Making informed ecosystem management decisions regarding global climate change comes with many challenges. Uncertainty surrounds the rates and magnitudes of change, due in part to the availability of data sources and the fact that many observations cannot be tied to a particular sampling station (Berliner 2003). Furthermore, considerable uncertainty arises from the fact that scientists have not yet solidified their understanding of many of the driving forces behind climate change models. A further area of uncertainty arises from not knowing how humans will continue to impact the Earth. Future use of fossil fuels, land-use change, and population increases are all variables, and they are largely dependent on societal decisions.

Recent climate change has the capability to dramatically alter the state and functioning of natural ecosystems. Much more must be learned quickly about the functioning of and the change in these systems in order to mitigate damage. By improving our understanding of natural ecosystems and their links to climate, we can be better prepared to properly manage our resources for future generations.

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See also Biodiversity; Biodiversity Hotspots; Carrying Capacity; Coastal Management; Complexity Theory; Ecological Forecasting; Food Webs; Human Ecology; Nitrogen Saturation; Regime Shifts; Resilience; Safe Minimum Standard (SMS)

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