Global climate change

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Global climate change, which is driven by human activity and natural variability, refers to the change in the mean state and/or variability of the climate system at decadal timescales and includes changes in temperature, precipitation, and atmospheric circulation patterns (IPCC 2013). Observations of recent global-scale changes in the climate system can be placed into a broader temporal context through comparison with the geologic record, which in turn can provide insight into sensitivity of the climate system to various natural and anthropogenic forcings and serve to provide baselines against which projections of future climates can be compared. Knowledge of global climate change requires consideration and associated impacts. Documenting the causes and consequences of global climate change requires knowledge of the spatial and temporal patterns and the biophysical processes responsible for driving past, present, and potential future climate change and climate change-related impacts.

Observed changes in the global climate system

Global-scale observations of the climate system, based on instrumental records and remote sensing, provide detailed records of changes in the climate system that extend from the mid-nineteenth century to the present. These direct measurements document the response of the atmosphere, oceans, sea level, cryosphere, and land surface to recent climate change at seasonal, annual, and decadal timescales. The observed globally averaged combined land surface and ocean surface temperature anomaly for the interval between 1880 CE and 2012 is 0.85 °C, with nearly the entire surface of the Earth experiencing warming during the twentieth and early twenty-first centuries. Fourteen of the fifteen warmest years on record have occurred during the twenty-first century (see Figure 1), with a strong likelihood that 2014 is the warmest year since 1880 CE. In addition, the diurnal temperature range (defined as the difference between daily maximum and daily minimum temperatures) has decreased during the latter half of the twentieth century and the incidence of extreme weather events (heatwaves, heavy precipitation, droughts) has increased for the majority of Earth's surface during recent decades. Approximately 60% of the net energy increase in the climate system between 1971 and 2010 CE has been stored in the upper 700 m of the ocean, resulting in the temperature of the upper 75 m of ocean increasing at a rate of 0.11 °C/decade during this interval. Ice sheets, alpine glaciers, and sea ice have experienced notable reductions in extent and/or volume since the 1970s. The average rate of ice loss from Greenland and Antarctic ice sheets has increased from 34 to 215 gigatons (Gt) year^{-1} and from 30 to 147 Gt year^{-1}, respectively, between 1992 and 2001 CE and 2002 and 2011 CE. The extent of the summer sea ice minimum in the Arctic Ocean decreased at a rate of between 9.4% and 13.6% per decade between 1979 and 2012 CE. Satellite, tide gauge, and documentary data

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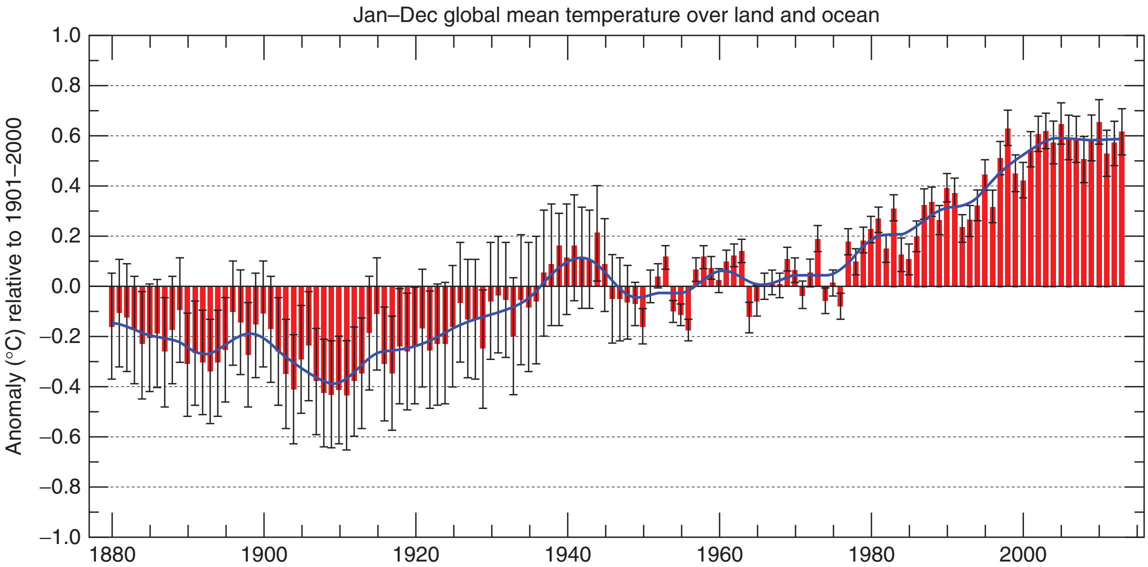

Figure 1 The annual trend in average global air temperature through December 2013. For each year, the red vertical bars indicate the range of uncertainty. The blue line tracks the changes in the trend over time (NOAA 2014).

indicate that the mean rate of globally average sea level rise was 1.7 mm $year^{-1}$ between 1901 and 2010 CE. The rate of sea level rise has been increasing in recent decades, with the rate nearly doubling to 3.2 mm $year^{-1}$ between 1993 and 2010 CE. The observed rise in sea level is largely attributable to glacier mass loss and the thermal expansion of ocean water. Other components of the Earth's biophysical environment that have been influenced by global climate change include river discharge, permafrost temperature, and biogeochemical cycles. Some of these changes have the potential to further amplify warming. For example, elevated temperatures in high northern latitudes have accelerated rates of thaw and aerobic and anaerobic decomposition in permafrost, facilitating the increased release of carbon dioxide and methane, which in turn acts to further augment radiative forcing (RF) (Hodgkins *et al.* 2014). It is important to note that methane is approximately 20 times more potent than CO_2 in terms of radiative forcing over a 100-year period, and therefore has the potential to greatly accelerate warming.

Drivers and attribution of recent climate change

Changes in the concentrations of greenhouse gases, aerosols, land cover, and solar radiation influence the Earth's energy balance and are considered to be the major drivers of observed climate change. Total anthropogenic radiative forcing in 2011 CE is 2.29 W m^{-2} relative to preindustrial (1750 CE) conditions. Currently, the most significant driver of recent climate change, in terms of radiative forcing, is the increase in the concentration of greenhouse gases, the most important of which is carbon dioxide (CO_2). The concentration of CO_2, which at the end of 2014 CE stood at 396 parts per million (ppm),

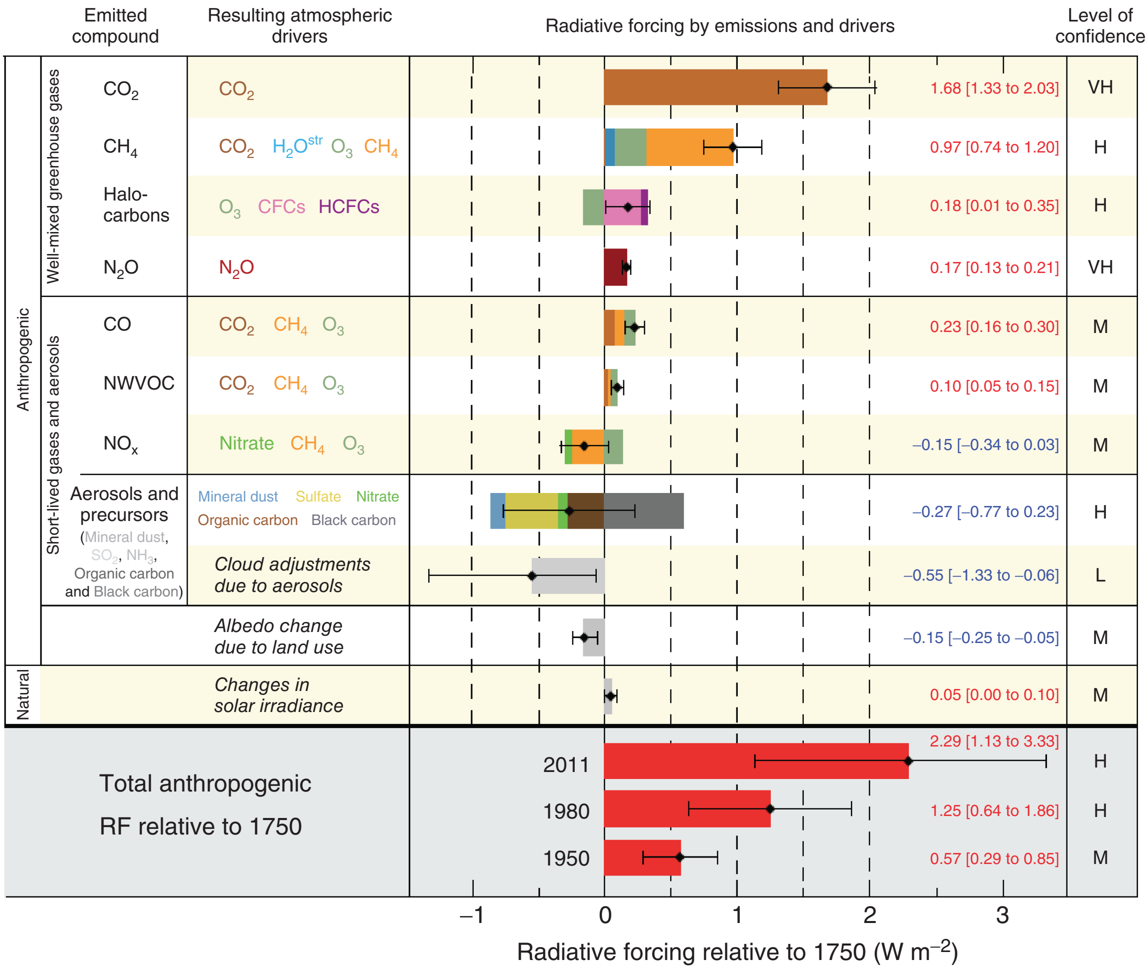

Figure 2 Radiative forcing estimates in 2011 relative to 1750 CE and aggregated uncertainties for the main drivers of climate change (IPCC 2013). VH, very high; H, high; M, medium; L, low.

is approximately 40% greater than its preindustrial concentration of 280 ppm. The current concentrations of the other major greenhouse gases, methane (CH_4) and nitrous oxide (N_2O), are 1893 parts per billion (ppb) and 326 ppb, and 150% and 20% greater than preindustrial levels, respectively. The well-mixed greenhouse gases (CO_2, CH_4, N_2O, and halocarbons) are responsible for an increase in radiative forcing of 2.83 W m^{-2} relative to 1750 CE (see Figure 2). It is important to note that ice core records indicate that the current concentrations of CO_2, CH_4, and N_2O are higher than at any time during the last 800 000 years, and exceed natural variability. The rate of increase in these greenhouse gases in recent decades is unmatched in the last 22 ka (IPCC 2013). An increase in planetary albedo, due to altered land use, increased emission of aerosols, and aerosol–cloud interactions, which act to counteract the influence of greenhouse gases on global mean radiative forcing, have limited the rate and magnitude of recent warming. Attribution studies have identified that anthropogenic activities are responsible for more than 50% of the observed increase in global mean surface temperature and have substantially contributed to the observed increase in global mean sea level, ocean acidification, and a reduction in Arctic sea-ice extent since the 1970s.

Past climates: placing recent climate change in context

The instrumental record (<150 years) is too short to adequately document the full range of climatic behavior and variability. Extending the observed record further back in time through the use of natural archives such as ice cores, marine and lake sediments, corals, tree rings, speleothems, and glacial deposits places observed changes in the global climate system during the twentieth and twenty-first centuries into a broader temporal context and provides evidence of longer-term climate change and variability at centennial to millennial scales. In doing so, the paleoclimate record enables an assessment of how unusual the rate of recent warming is. For example, analyses of multiple proxies extracted from marine sediment and ice core records indicate that the past 2.6 million years of Earth's climate history have been characterized by repeated cycles of glacial advance and retreat. These cycles, which are driven by changes in Earth's orbital elements, result in the spread of continental ice sheets in the Northern Hemisphere, the expansion of alpine glaciers and sea ice globally, and significant changes in sea level. During the Last Glacial Maximum (LGM), which occurred at 21 ka BP, global sea level and mean temperature were approximately 120 m and 4 °C lower than at present, respectively. The geologic record can also be used to document rates of change associated with past climate change events. For example, the Paleocene–Eocene Thermal Maximum (PETM) involved an initial increase in global temperature of 5 °C that occurred over approximately 10 000 years (Diffenbaugh and Field 2013); this rate of warming is 1–2 orders of magnitude slower than the rate of warming projected to occur this coming century. Rates of change associated with the most recent glacial–interglacial transition, the Medieval Climate Anomaly and the Little Ice Age are all lower than the current and projected rates of change. Increasingly, climate scientists are concerned about the potential of abrupt climate change, which occurs when the climate system crosses a threshold or "tipping point," and responds in a nonlinear fashion at rates that exceed the initial forcing (NRC 2013). Importantly, the paleoclimate record documents the existence of abrupt changes in global climate during the most recent glacial–interglacial transition. These events, the largest of which is the Younger Dryas, a millennial-length cold period that resulted from an abrupt change in Atlantic Meridional Overturning Circulation, led to a return to near-glacial conditions between 12.9 ka and 11.6 ka through much of the high latitudes of the Northern Hemisphere. Proxy-based paleoclimate data can also be used to test and verify the output of coupled ocean–atmosphere global climate models, simulating the response of the climate system to large changes in boundary conditions and forcings. Proxy and model-based studies documenting the expression of these abrupt climate change events provide valuable insight into the response of ocean and atmospheric circulation to climate forcing, and the resulting impacts of these changes on the structure, function, and composition of terrestrial and aquatic ecosystems. Other areas of concern related to abrupt change include the behavior of the ocean (acidification, oxygen concentration); atmospheric circulation (El Niño Southern

Oscillation, North Atlantic Oscillation, Pacific Decadal Oscillation); global biogeochemical cycles (CO_2, CH_4), especially at high latitudes; sea-ice extent; and land-cover change.

Impacts associated with recent climate change

Impacts of climate change are widespread and include changes in the biophysical environment, phenology, species distribution and abundance, habitat availability, agricultural productivity, and the spread of infectious disease. Reductions in the volume and extent of alpine glaciers have influenced downstream freshwater availability, especially in mid- and low latitude regions, where the need for fresh water is increasing. Populations in mid- and low latitude regions are highly dependent on glacier meltwater for consumption, irrigation, and hydropower generation during the dry season, and as a result are susceptible to global climate change induced alterations of mountain hydroclimate. Earlier snowmelt also leads to reduced late summer stream flow, which negatively affects aquatic ecosystems, lowers the groundwater tables, and lengthens the fire season. However, it is important to recognize that the societal impacts associated with climate change are expressed differentially due to the varying exposure and vulnerabilities of populations to climatic and nonclimatic factors. For example, multidimensional inequalities in socioeconomic status and income, resulting from uneven development, influence the magnitude, risk, exposure, and vulnerability of various groups to current and future climate change (Richardson, Steffen, and Liverman 2011). The increase in the atmospheric concentration of CO_2 has resulted in ocean acidification. The decrease of ocean surface water pH of 0.1, which has occurred since the Industrial Revolution, negatively influences calcifying marine organisms. Changes in phenology, or the timing of life-history events, have been attributed to recent climate change. For example, in response to elevated temperatures, the growing season has lengthened by approximately two weeks in the mid- to high northern latitudes during the late twentieth and early twenty-first centuries. A lengthening of the growing season can influence trophic relations and result in trophic mismatches, such as the timing of migration, breeding, and/or food availability. Shifts in regional climate and the varying velocity of these climate shifts can also influence biotic interactions, species distribution, and community structure through competitive displacement, increased predation, or altered predator–prey relationships (Blois *et al*. 2013). Global climate change also influences the provision of ecosystem services (Nelson *et al*. 2013), with the provision, timing, and location of ecosystem services such as nutrient cycling, wildfire regulation, fisheries productivity, coastal flood protection, and water supply altered both negatively and positively by global climate change. Agriculture will be heavily affected by global climate change, with crop growth and quality, livestock health, and pests all potentially influenced by changing climate (temperature and precipitation) and extreme weather events, which in turn may threaten global food security. For example, increases in growing season temperatures may lead to decreases in crop and livestock production and yields through increasing pressures from pests, weeds, and pathogens. Changes in precipitation patterns may lead to periodic crop failures and contribute to long-lasting declines in crop yields, requiring shifts in the crops and livestock raised in particular regions (Thornton *et al*. 2014). Changes in climate and the resultant shifts in ecological conditions may facilitate the spread of pathogens, parasites, and food-, water-, and animal-borne diseases. For example, the spread of vector-borne infectious disease as a result of the direct and indirect effects of climate change is an area of increasing concern. As temperature increases, the latitudinal and elevational range of the vectors responsible for transmitting malaria (*Anopheles* mosquito) and Dengue fever (*Aedes aegypti* mosquito) will expand and increase the human population exposed to the parasites responsible for these diseases. It is also expected that the incidence of waterborne infections, such as cholera, that result in diarrheal distress will increase as untreated runoff and/or sewage, associated with extreme precipitation events, enters the water supply (Altizer *et al.* 2013).

Projections of future climate

Coupled ocean–atmosphere global climate models are used to simulate the Earth's climate system, investigate the sensitivity of the climate system to various forcings, and project changes in temperature and precipitation regimes in the future under various scenarios. The scenarios used to guide the climate models that form the basis for the global and regional climate projections presented in the most recent Intergovernmental Panel on Climate Change assessment report (IPCC 2013) are referred to as representative concentration pathways (RCPs). The four RCPs (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) which reflect the radiative forcings (in W/m^2) associated with four potential greenhouse gas concentration trajectories consistent with physical, demographic, and socioeconomic constraints, describe four possible climate futures. The RCP2.6 scenario characterizes a climate future in which strong reductions in greenhouse gas emissions occur and radiative forcing peaks in the mid-twenty-first century and declines by 2100 CE. The RCP8.5 scenario, which is most similar to the trajectory we are currently following, characterizes a climate future where greenhouse gas emissions continue to increase throughout the twenty-first century. It is important to note that the choice of RCP scenario greatly influences the magnitude of the projected changes in global temperature as early as the middle of the twenty-first century. By the end of the twenty-first century, global mean surface temperatures are projected to exceed 1.5 °C relative to the 1850–1900 CE mean global surface temperature for all RCP scenarios except RCP2.6. Under all scenarios high latitude and high elevation regions are expected to warm at a considerably faster rate than low latitude regions (see Figure 3). For example, the RCP8.5 climate model simulations indicate that the warming experienced at high northern latitudes will exceed 4 °C relative to the 1985–2005 CE midway through the twenty-first century, and that the warming in these same regions will exceed 6 °C by 2100 CE (Diffenbaugh and Field 2013). Precipitation patterns are expected to show greater spatial variability relative to temperature, with the contrast between wet and dry regions and wet and dry seasons increasing during the twenty-first century. Ocean circulation and acidity will be influenced by the increase in ocean heat content and the partial pressure of atmospheric CO_2, respectively. Continued reductions in global glacial ice volume, sea ice, and snow cover, together with the thermal expansion of ocean water, will contribute to a projected sea level rise of between 28 cm and 98 cm by 2100 CE. The occurrence, duration, and timing of extreme weather and climate events and variability in weather patterns are all projected to increase as the planet warms. For example, most land areas will experience notable increases in the frequency of extreme hot seasons for over 80% of years, with mean summer temperatures above

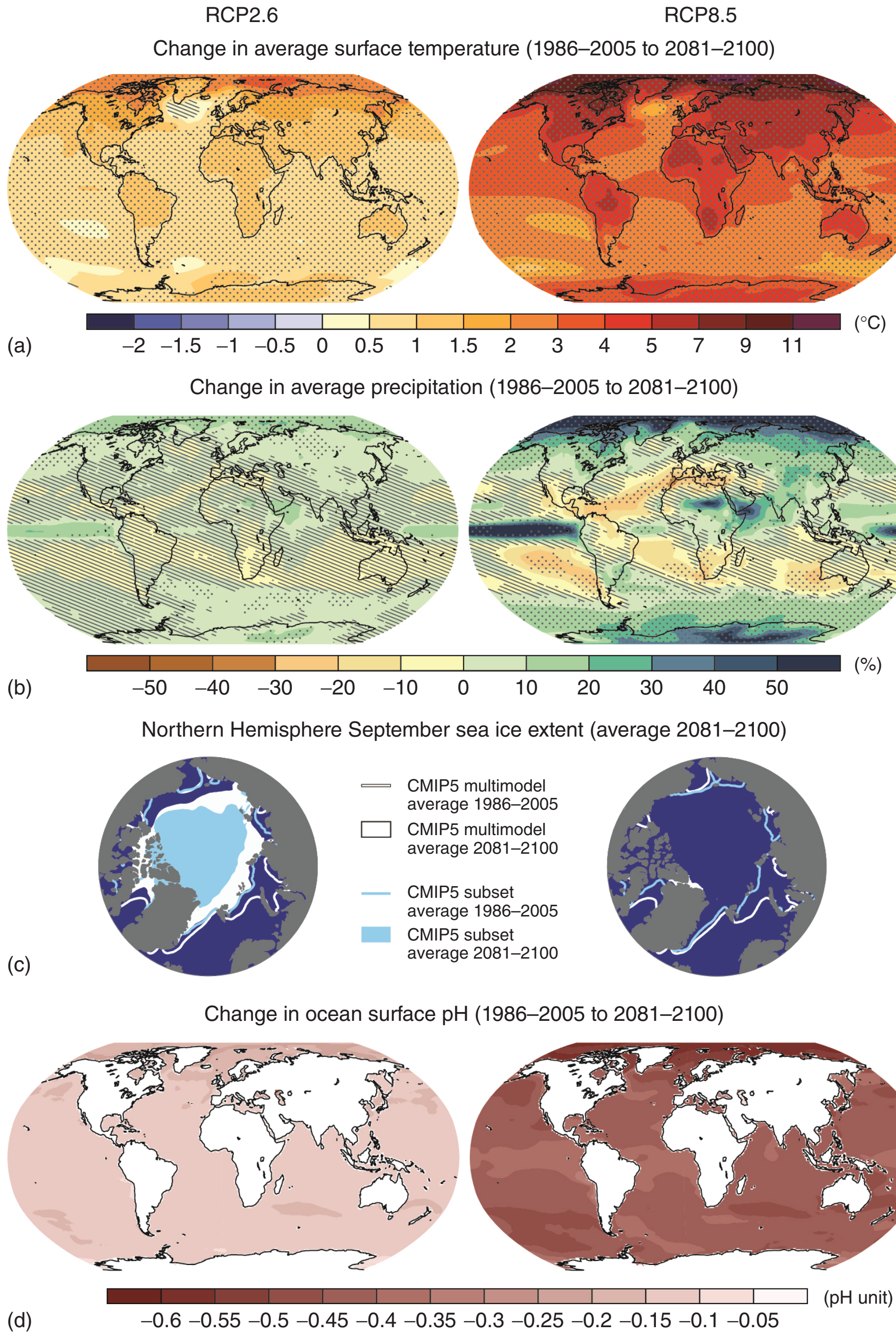

Figure 3 Map of CMIP5 multimodel mean results for the scenarios RCP2.6 and RCP8.5 in 2081–2100 of annual mean surface temperature (IPCC 2013).

the late-twentieth-century maximum by 2100 CE (Diffenbaugh and Field 2013). It is expected that improvements in the parameterization of clouds, ground hydrology, ocean–atmosphere interactions, and the inclusion of models that incorporate the dynamic behavior of ice sheets, and refinements to ocean and terrestrial biogeochemical cycles, will serve to better constrain climate projections in the future.

SEE ALSO: Climate change and biogeography; Global climate change; Global climate models; Intergovernmental Panel on Climate Change (IPCC); Oceans and climate; Paleoclimatology; Paleoecology

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