Climate Change

An Information Statement of the American Meteorological Society

(Adopted by the AMS Council on 15 April 2019)

The AMS Information Statement seeks to provide a trustworthy, objective, and scientifically up-to-date explanation of climate change to the public using easily understood language.

Background

This statement provides an overview of how and why global climate has changed over the past century and why it will continue to change in the future. It is based on peer-reviewed scientific literature and reflects current scientific understanding. A particular focus is on climate change in recent decades and its connection to human-produced greenhouse gases.

Executive Summary

Research has found a human influence on the climate of the past several decades. Its manifestation includes the warming of the atmosphere and oceans, intensification of the heaviest precipitation over continental areas, increasing upper-ocean acidity, increasing frequency and intensity of daily temperature extremes, reductions in Northern Hemisphere snow and ice, and rising global sea level. The latitudinal and seasonal observations of the surface warming and the observed warming of the troposphere and cooling of the stratosphere are consistent with theoretical expectations from increased concentrations of greenhouse gases.

The increase in global average surface temperature over the past half-century cannot be fully explained by natural climate variability, e.g., responses to Earth's orbital changes over thousands of years, or natural climate forcing such as from solar or volcanic variability. The observed warming rate varies from place to place and from decade to decade because of natural climate variations, such as natural swings between El Niño and La Niña on time scales of two to seven years, and variations in ocean circulation in the Pacific and Atlantic basins on decadal to multi-decadal timescales. The influence of these relatively short-period fluctuations is factored into climate change analyses. These natural fluctuations have neither the magnitude nor the spatial characteristics to explain the observed warming of Earth's average surface temperature over the past several decades. The IPCC (2013), USGCRP (2017), and USGCRP (2018) indicate that it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-twentieth century.

Proxies, which are indirect measurements of past temperature obtained from archives, such as tree rings, corals, ice cores, lake and marine sediments, and cave stalagmites, reveal that the rate and magnitude of the current global temperature change is likely exceptional in the context of the last two thousand years. Global temperatures were last on par with the present ones in the previous Interglacial Period (125,000 years ago), when sea level was 6–9 m (20–30 ft) higher than today. Projected warming over the next century will likely place global temperatures in a range not seen in millions of years of geologic history.

How is climate changing?

Earth’s climate is warming. Observations show increasing surface air and ocean temperatures over most regions and diminishing snow and ice cover at high latitudes. Global surface temperature has increased at an average rate of 0.8°C (1.4°F) per century over the period 1901–2017, and 1.9°C (3.4°F) per century during 1979–2017. In addition to this long-term warming, the global surface temperature fluctuates from year to year and decade to decade from interactions of the atmosphere, ocean, land surface, and cryosphere (the snow and ice-covered portions of Earth); these processes represent natural climate variability. Consequently, not every year is warmer than the preceding one, globally: For example, 2011 was cooler than the ten previous years. However, the four warmest years on record through 2018 are the four most recent ones—2015, 2016, 2017, and 2018—with 2016 being the warmest.

The surface warming over northern continents is largest in the middle to high latitudes; it is pronounced in winter–spring and notably smaller in summer–autumn. Over North America, the winter–spring surface warming is largest in Alaska and central-northern Canada. The surface warming in the high southern latitudes is largest in spring (September–November), with warming over West Antarctica and the Ross Ice Shelf since 1979. The warming is apparent not just in seasonal temperatures: The United States has had twice as many record daily high maximum temperatures as record daily low minimum temperatures from 2000 into the late 2010s.

The warming is not confined to Earth’s surface: The troposphere—the region extending upward from the surface to about 10 km (30,000 ft) altitude—has also warmed. Although tropospheric temperature records are not as long or spatially dense as those at the surface—limiting the ability to characterize long-term trends—both the lower and middle troposphere have warmed, with the former warming more than the latter. Importantly, cooling is present in the stratosphere (the region directly above the troposphere)—which together with surface warming is consistent with the predicted response to increasing greenhouse gas concentrations.

The oceans, which cover about 70% of Earth’s surface, have warmed both at the surface and in the upper subsurface layers. Annual sea surface temperature has warmed notably (i.e., approaching or exceeding 1.0°C or 1.8°F per century) in the Barents and Kara Seas along the Arctic Rim, off the east coasts of Asia and northern North America, in the equatorial Indian Ocean, around the Southern Hemisphere continents, and across large stretches of the Southern Ocean. The cooling trends, in contrast, are small and spatially limited, confined to the North Atlantic near Greenland and the Amundsen and Bellingshausen Seas off the West Antarctic Ice Sheet. The heat content in the upper ocean (0–700 m; 0–2,300 ft) has also increased, notably in the North Atlantic, since at least the 1950s. There is also a strong positive heat content trend at middle oceanic depths (700–2,000 m; 2,300–6,500 ft).

In addition to the widespread warming, the oceans are becoming more acidic and the amount of dissolved oxygen is decreasing, impacting marine life. These changes are consequences of well-understood chemical and physical processes. Seawater becomes more acidic when it absorbs some of the excess carbon dioxide that has accumulated in the atmosphere. Observations show that the oceans have become 25% more acidic (0.1 pH decrease) over the last century. Ocean acidification affects marine organisms, notably those that build calcium carbonate structures, including shellfish, corals, and many species of marine plankton. Pervasive surface warming has led to reduced ocean oxygen levels that, when combined with coastal pollution, contribute to ocean “dead zones” and massive fish kills. An increase in the magnitude and duration of ocean temperature extremes represent an acute near-term threat to many marine ecosystems, including coral reefs, as apparent from the global-scale coral bleaching event of 2015–2016.

Globally averaged sea level is estimated to have risen by about 17 cm (6.7 in) during the twentieth century, with an acceleration evident since the early 1990s. The climate change–driven rate of sea level rise over the satellite altimeter era (1993–present) is about 2.9 mm/yr (0.1 in/yr). Regionally, the sea level rise can be larger or smaller depending on a number of factors, including vertical motion of the land itself (e.g., from tectonic activity, removal of groundwater, low-frequency changes in ocean circulation patterns, and adjustment due to past glaciations). Even small rises in sea level can be consequential for coastal communities and small island nations.

The cryosphere—regions on Earth where water is in the form of ice or snow—has changed significantly during the period of the instrumental record, including the large ice sheets on Greenland and Antarctica, alpine glaciers and small ice caps, terrestrial snow, and sea ice. Gravity-based satellite measurements of the 2002–2016 loss in ice sheet mass show that Greenland contributed to an equivalent sea level rise of about 0.75 mm/yr, and Antarctica to about 0.33 mm/yr; the loss rate for Greenland is more than three times larger than for the preceding decade. The global trend in the mass balance of alpine glaciers over the last century is equivalent to about 1 mm/yr of sea level rise. The loss of seasonal terrestrial snow (and ice), while not contributing significantly to sea level rise, influences the absorption of solar radiation, atmospheric boundary layer temperature and humidity, and freshwater storage. Multiple data sources indicate downward trends in Northern Hemisphere terrestrial snow cover extent and depth in late spring, which impact runoff—a key source of water in the western United States.

Arctic sea ice at its seasonal minimum in September has declined by about 13% per decade during 1979–2018, i.e., a 50% decline in extent over the preceding four decades, well beyond what can be expected from natural variability. On the other hand, Antarctic sea ice extent has increased in some regions while it has decreased in others. This hemispheric asymmetry in the response to rising greenhouse gases is not unexpected due to the large-scale upwelling of colder deep waters in the Southern Ocean, which limit the effects of surface-forced change.

Precipitation—a key link between the atmosphere, oceans, land surface, and the cryosphere—is increasing over the northern middle–high latitudes, especially in autumn. Over the United States, annual precipitation has decreased in the Southwest but increased over the Great Plains, Midwest, and the Northeast; U.S.-averaged precipitation has increased by about 4% since 1900, mostly from the increase in autumn precipitation. Heavy precipitation (e.g., maximum daily precipitation in consecutive 5-year segments) has increased in both intensity and frequency since 1900, especially in the eastern half of the United States and notably in the Northeast. Areas that receive limited precipitation, sometimes called drylands, are increasing in area. The combination of warmer temperature and reduced precipitation in some regions has increased the risk of drought and drought-related impacts. There is evidence that wildfire seasons are increasing globally and areas where wildfires occur are expanding.

The number and intensity of Atlantic hurricanes have both increased since the early 1980s, but much of this increase may be due to natural variability of the atmosphere and ocean. Furthermore, there is little trend or even a decrease in hurricane activity in other ocean basins, so the global trend, if there is one, is not clear. There is evidence that ocean warming is providing more energy to make hurricanes more intense.

There is no sign of an increase in the most violent U.S. tornadoes (those rated EF4 or EF5 on the Enhanced Fujita Scale). However, there is evidence that annual U.S. tornado activity has become more variable since the 1970s, with larger tornado outbreaks separated by longer periods of below-average tornado frequency. Because of the wide range of natural variability in tornadoes, severe thunderstorms, and other localized weather events, it may take longer for any persistent changes related to human-produced greenhouse gases to become detectable.

Why is climate changing?

Climate—the statistical description (both mean and variability) of the atmosphere–ocean–land–cryosphere system over a few decades—is characterized by the balance of incoming and outgoing energy, which strongly depends on the composition of the atmosphere. Consequently, climate can be affected by human-induced changes in atmospheric composition (greenhouse gases and aerosols) and land surface use/cover. Climate is also influenced by natural variability, which includes decadal to multi-decadal fluctuations of ocean circulation and temperature in the Atlantic and Pacific basins.

Anthropogenic (i.e., human-induced) climate change cannot be accurately characterized from linear trends over short periods, as these trends will likely have contributions from the incomplete cycles of natural decadal to multi-decadal variability. However, many of the above-noted changes in the past 120 years cannot be fully accounted for by natural climate variability such as the decadal to multi-decadal fluctuations of ocean circulation and temperature in the Atlantic and Pacific basins. Scientific evidence indicates that the leading cause of climate change in the most recent half century is the anthropogenic increase in the concentration of atmospheric greenhouse gases, including carbon dioxide (CO_2), chlorofluorocarbons, methane, tropospheric ozone, and nitrous oxide.

Other than water vapor, the most prevalent greenhouse gas is CO_2, whose concentration is rising mainly from fossil fuel combustion, cement production, and deforestation. About half the anthropogenic CO_2 input into the atmosphere has remained in the atmosphere, and the rest has been taken up by the oceans and terrestrial biosphere (i.e., soil and plants on land)—the two CO_2 reservoirs with which the atmosphere routinely exchanges large amounts of CO_2, seasonally. Once introduced, the CO_2 can reside in the atmosphere for 1000 years or more before it is removed by natural processes, with more than 50% of the introduced CO_2 remaining in the atmosphere for at least 50 years and roughly 30% remaining for at least 100 years.

Water vapor is another important greenhouse gas, but unlike CO_2, it responds quickly to temperature change. For this reason, it mostly acts as a feedback, amplifying the response of the climate system to changes in radiative forcing, for instance from long-lived greenhouse gases like CO_2.

A third important greenhouse gas is methane, which is produced both naturally, primarily by emissions from wetlands and wildlife, and from human activities such as agriculture, landfills, and fossil fuel extraction processes, with the human activities responsible for the majority of emissions today. For example, methane is a by-product of the hydraulic fracturing (fracking) process for extracting oil and natural gas from underground. Methane is shorter-lived and much less abundant than CO_2 but a much more effective greenhouse gas per molecule, with more than 30 times the warming potential of CO_2 by weight when compared over a 100-year period. The concentration of methane in the atmosphere was less than 800 parts per billion before the industrial revolution and is now measured at over 1,800 parts per billion. As the climate changes, the production of natural methane will likely increase, for example, due to thawing of previously frozen carbon-rich soils in the permafrost zones of the high-latitude continents and the possible mobilization of methane trapped in hydrate form in oceanic sediment.

Human activity also affects climate through changes in the number and physical properties of tiny (nano- to micrometer diameter) solid particles and liquid droplets suspended in the atmosphere, known collectively as atmospheric aerosols, e.g., dust and sulfates from air pollution. Aerosols modify both visible and infrared radiation and can influence the spatial distribution of clouds and precipitation. Most aerosols originating from human activity act to cool the planet, partly counteracting the greenhouse warming. However, the time span in which aerosols remain suspended in the troposphere is much shorter than for greenhouse gases such as CO_2. Stratospheric aerosols generated by occasional large sulfur-rich volcanic eruptions can reduce the global surface temperature for a few years.

Changes in land surface use from agriculture, irrigation, deforestation, and urbanization also influence the surface exchange of water and energy with the atmosphere, generating regional climate change.

How can climate change be projected into the future?

Climate projections for decades into the future are made using computer programs that model the atmosphere–ocean–land surface–cryosphere system, based largely on fundamental physical laws and well-understood physical principles. These models explicitly simulate the large-scale [approximately 100 km (60 miles) or larger] motions of the atmosphere and ocean. By subjecting these models to time-dependent greenhouse gas concentrations and other forcings, with concentrations allowed to evolve in the future based on emission hypotheses (or "scenarios"), the simulated climate responds to such changes in atmospheric composition. Climate projections from such calculations focus on identifying the average (mean) state and extreme states of the atmosphere and ocean, summarized on the time scales of decades, rather than an instantaneous future state of the entire system. The projections depend on the evolution of the energy budget and its influence on the climate system's slowly varying system components—ocean, land surface, and the cryosphere—and their interactions.

Natural variability can obscure anthropogenic influences on climate at the multidecadal scale. Examples include a slower pace of atmospheric warming during the first decade of the twenty-first century and a more rapid pace during the mid-2010s. Such changes in the pace of warming are also seen in projections of future climate.

Climate models have both strengths and weaknesses. For example, they reliably represent many of the fundamental processes that govern weather and climate, including midlatitude storms, heat waves, droughts, and extreme seasonal precipitation. As a result, many models are able to simulate the broad features of the twentieth-century climate. However, some crucial processes like clouds and convection, ocean eddies, deep water formation, and carbon cycle remain crudely represented. These deficiencies are thought to underpin model errors in the representation of the present climate, its modes of natural variability, and its recent evolution. Climate simulations and projections are especially challenged on the regional scale—the scale of relevance in adaptation efforts. However, climate models successfully replicate the global warming of the twentieth century, and they agree that further warming and other global and regional changes can be expected this century. Furthermore, there are recent developments of higher-resolution climate models that can be used to project regional-scale changes.

How is the climate projected to change in the future?

Based on understanding of past changes and projections of future human activities, it is projected that over the next 100 years Earth's surface will warm at least as much as it did in the past 100 years, and perhaps 2–6 times more. Further, the proportion of global warming that is offset by cooling from human sources of aerosols may diminish in the future.

Global warming and sea level rise would continue during the next few decades even if atmospheric greenhouse gas concentrations could somehow be held constant at their present levels. This decades-long delay is because of the inherent slowness with which the oceans and polar ice sheets respond to surrounding temperature, the input of heat, and changes in the chemistry of the air and oceans.

Climate models project the global average sea level to be 0.3–1.2 m (1.0–4.0 ft) higher, and the global average surface temperature to be warmer by more than 1.5°C (and up to 4.0°C depending on future emission scenarios) at the end of the twenty-first century relative to the 1850–1900 period. A narrower range for the global surface temperature increase (2.6°–3.1°C) is obtained in scenarios where emissions are restricted to the level of current international agreements. Oceans are also projected to be significantly more acidic (an additional 0.3–0.4 pH decrease, or +150% more acidic) by the end of this century.

At regional scales, climate models project a general reduction of precipitation in the subtropics, which, together with warmer temperatures, will have the effect of intensifying drought. An increase of precipitation in the high latitudes is also projected, with associated increasing extreme precipitation events. The sea ice in the Arctic Ocean is projected to become seasonal or disappear entirely from some places, making the continental margins of the Arctic more prone to damaging storms and ocean waves. Warming in Alaska, which is faster than in other parts of the United States, will continue, with likely further thawing of permafrost.

Barring large increases in volcanic activity or decreases in solar energy output, reducing the amount of greenhouse gas emitted by human activity and/or accelerating the removal of these gases from the atmosphere is the only way to avoid much of the projected warming and its associated global-scale effects on sea level rise, precipitation and heat extremes, and ecosystem health. Adaptation could ameliorate at least some of the impacts of projected climate change on economies and human health.

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