How We Know Global Warming is Real
The science behind human-induced climate change
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Atmospheric carbon dioxide concentrations are higher today than at any time in at least the past 650,000 years. They are about 35% higher than before the industrial revolution, and this increase is caused by human activities, primarily the burning of fossil fuels.

Carbon dioxide is a greenhouse gas, as are methane, nitrous oxide, water vapor, and a host of other trace gases. They occur naturally in the atmosphere. Greenhouse gases act like a blanket for infrared radiation, retaining radiative energy near the surface that would otherwise escape directly to space. An increase in atmospheric concentrations of carbon dioxide and of other greenhouse gases augments the natural greenhouse effect; it increases the radiative energy available to Earth's surface and to the lower atmosphere. Unless compensated for by other processes, the increase in radiative energy available to the surface and the lower atmosphere leads to warming. This we know. How do we know it?

How do we know carbon dioxide concentrations have increased?

The concentrations of carbon dioxide and other greenhouse gases in atmospheric samples have been measured continuously since the late 1950s. Since then, carbon dioxide concentrations have increased steadily from about 315 parts per million (ppm, or molecules of carbon dioxide per million molecules of dry air) in the late 1950s to about 385 ppm now, with small spatial variations away from major sources of emissions. For the more distant past, we can measure atmospheric concentrations of greenhouse gases in bubbles of ancient air preserved in ice (e.g., in Greenland and Antarctica). Ice core records currently go back 650,000 years; over this period we know that carbon dioxide concentrations have never been higher than they are now. Before the industrial revolution, they were about 280 ppm, and they have varied naturally between about 180 ppm during ice ages and 300 ppm during warm periods. Concentrations of methane and nitrous oxide have likewise increased since the industrial revolution and, for methane, are higher now than they have been in the 650,000 years before the industrial revolution.

How do we know the increase in carbon dioxide concentrations is caused by human activities?

There are several lines of evidence. We know approximately how much carbon dioxide is emitted as a result of human activities. Adding up the human sources of carbon dioxide—primarily from fossil fuel burning, cement production, and land use changes (e.g., deforestation)—one finds that only about half the carbon dioxide emitted as a result of human activities has led to an increase in atmospheric concentrations. The other half of the emitted carbon dioxide has been taken up by oceans and the biosphere—where and how exactly is not completely understood: there is a "missing carbon sink."

Human activities thus can account for the increase in carbon dioxide concentrations. Changes in the isotopic composition of carbon dioxide show that the carbon in the added carbon dioxide derives largely from plant materials, that is, from processes such as burning of biomass or fossil fuels, which are derived from fossil plant materials. Minute changes in the atmospheric concentration of oxygen show that the added carbon dioxide derives from burning of the plant materials. And concentrations of carbon dioxide in the ocean have increased along with the atmospheric concentrations, showing that the increase in atmospheric carbon dioxide concentrations cannot be a result of release from the oceans. All lines of evidence taken together make it unambiguous that the increase in atmospheric carbon dioxide concentrations is human induced and is primarily a result of fossil fuel burning. (Similar reasoning can be evoked for other greenhouse gases, but for some of those, such as methane and nitrous oxide, their sources are not as clear as those of carbon dioxide.)

How can such a minute amount of carbon dioxide affect Earth's radiative energy balance?

Concentrations of carbon dioxide are measured in parts per million, those of methane and nitrous oxide in parts per billion. These are trace constituents of the atmosphere. Together with water vapor, they account for less than 1% of the volume of the atmosphere. And yet they are crucially important for Earth's climate.

Earth's surface is heated by absorption of solar (shortwave) radiation; it emits infrared (longwave) radiation, which would escape almost directly to space if it were not for water vapor and the other greenhouse gases. Nitrogen and oxygen, which account for about 99% of the volume of the atmosphere, are essentially transparent to infrared radiation. But greenhouse gases absorb infrared radiation and re-emit it in all directions. Some of the infrared radiation that would otherwise directly escape to space is emitted back toward the surface. Without this natural greenhouse effect, primarily owing to water vapor and carbon dioxide, Earth's mean surface temperature would be a freezing -1°F, instead of the habitable 59°F we currently enjoy. Despite their small amounts, then, the greenhouse gases strongly affect Earth's temperature. Increasing their concentration augments the natural greenhouse effect.

How do increases in greenhouse gas concentrations lead to surface temperature increases?

Increasing the concentration of greenhouse gases increases the atmosphere's "optical thickness" for infrared radiation, which means that more of the radiation that eventually does escape to space comes from higher levels in the atmosphere. The mean temperature at the level from which the infrared radiation effectively escapes to space (the emission level) is determined by the total amount of solar radiation absorbed by Earth. The same amount of energy Earth receives as solar radiation, in a steady state, must be returned as infrared radiation; the energy of radiation depends on the temperature at which it is emitted and thus determines the mean temperature at the emission level. For Earth, this temperature is -1°F—the mean temperature of the surface if the atmosphere would not absorb infrared radiation. Now, increasing greenhouse gas concentrations implies raising the emission level at which, in the mean, this temperature is attained. If the temperature decreases between the surface and this level and its rate of decrease with height does not change substantially, then the surface temperature must increase as the emission level is raised. This is the greenhouse effect. It is also the reason that clear summer nights in deserts, under a dry atmosphere, are colder than cloudy summer nights on the U.S. east coast, under a relatively moist atmosphere.

In fact, Earth surface temperatures have increased by about 1.3°F over the past century. The temperature increase has been particularly pronounced in the past 20 years (for an illustration, see the animations of temperature changes at www.gps.caltech.edu/~tapio/discriminants/animations.html). The scientific consensus about the cause of the recent warming was summarized by the Intergovernmental Panel on Climate Change (IPCC) in 2007: "Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. … The observed widespread warming of the atmosphere and ocean, together with ice mass loss, support the conclusion that it is extremely unlikely that global climate change of the past 50 years can be explained without external forcing, and very likely that it is not due to known natural causes alone."

The IPCC conclusions rely on climate simulations with computer models. Based on spectroscopic measurements of the optical properties of greenhouse gases, we can calculate relatively accurately the impact increasing concentrations of greenhouse gases have on Earth's radiative energy balance. For example, the radiative forcing owing to increases in the concentrations of carbon dioxide, methane, and nitrous oxide in the industrial era is about 2.3 Watts per square meter. (This is the change in radiative energy fluxes in the lower troposphere before temperatures have adjusted.) We need computer models to translate changes in the radiative energy balance into changes in temperature and other climate variables because feedbacks in the climate system render the climate response to changes in the atmospheric composition complex, and because other human emissions (smog) also affect climate in complex ways. For example, as the surface and lower atmosphere warm in response to increases in carbon dioxide concentrations, the atmospheric concentration of water vapor near the surface increases as well. That this has to happen is well established on the basis of the energy balance of the surface and relations between evaporation rates and the relative humidity of the atmosphere (it is not directly, as is sometimes stated, a consequence of higher evaporation rates). Water vapor, however, is a greenhouse gas in itself, and so it amplifies the temperature response to increases in carbon dioxide concentrations and leads to greater surface warming than would occur in the absence of water vapor feedback. Other feedbacks that must be taken into account in simulating the climate response to changes in atmospheric composition involve, for example, changes in cloud cover, dynamical changes that affect the rate at which temperature decreases with height and hence affect the strength of the greenhouse effect, and surface changes (e.g., loss of sea ice). Current climate models, with Newton's laws of motion and the laws of thermodynamics and radiative transfer at their core, take such processes into account. They are able to reproduce, for example, Earth's seasonal cycle if all such processes are taken into account but not, for example, if water vapor feedback is neglected. The IPCC's conclusion is based on the fact that these models can only match the observed climate record of the past 50 years if they take human-induced changes in atmospheric composition into account. They fail to match the observed record if they only model natural variability, which may include, for example, climate responses to fluctuations in solar radiation.

Climate feedbacks are the central source of scientific (as opposed to socio-economic) uncertainty in climate projections. The dominant source of uncertainty are cloud feedbacks, which are incompletely understood. The area covered by low stratus clouds may increase or decrease as the climate warms. Because stratus clouds are low, they do not have a strong greenhouse effect (the strength of the greenhouse effect depends on the temperature difference between the surface and the level from which infrared radiation is emitted, and this is small for low clouds); however, they reflect sunlight, and so exert a cooling effect on the surface, as anyone knows who has been near southern California's coast on an overcast spring morning. If their area coverage increases as greenhouse gas concentrations increase, the surface temperature response will be muted; if their area coverage decreases, the surface temperature response will be amplified. It is currently unclear how these clouds respond to climate change, and climate models simulate widely varying responses. Other major uncertainties include the effects of aerosols (smog) on clouds and the radiative balance and, on timescales longer than a few decades, the response of ice sheets to changes in temperature.

Uncertainties notwithstanding, it is clear that increases in greenhouse gas concentrations, in the global mean, will lead to warming. Although climate models differ in the amount of warming they project, in its spatial distribution, and in other more detailed aspects of the climate response, all climate models that can reproduce observed characteristics such as the seasonal cycle project warming in response to the increases in greenhouse gas concentrations that are expected in the coming decades as a result of continued burning of fossil fuels and other human activities such as tropical deforestation. The projected consequences of the increased concentrations of greenhouse gases have been widely publicized. Global-mean surface temperatures are likely to increase by 2.0 to 11.5°F by the year 2100, with the uncertainty range reflecting scientific uncertainties (primarily about clouds) as well as socio-economic uncertainties (primarily about the rate of emission of greenhouse gases over the 21st century). Land areas are projected to warm faster than ocean areas. The risk of summer droughts in mid-continental regions is likely to increase. Sea level is projected to rise, both by thermal expansion of the warming oceans and by melting of land ice.

Less widely publicized but important for policy considerations are projected very long-term climate changes, of which some already now are unavoidable. Even if we were able to keep the atmospheric greenhouse gas concentration fixed at its present level—this would require an immediate and unrealistically drastic reduction in emissions—the Earth surface would likely warm by another 0.9–2.5°F over the next centuries. The oceans with their large thermal and dynamic inertia provide a buffer that delays the response of the surface climate to changes in greenhouse gas concentrations. The oceans will continue to warm over about 500 years. Their waters will expand as they warm, causing sea level rise. Ice sheets are thought to respond over timescales of centuries, though this is challenged by recent data from Greenland and Antarctica, which show evidence of a more rapid, though possibly transient, response. Their full contribution to sea level rise will take centuries to manifest. Studies of climate change abatement policies typically end in the year 2100 and thus do not take into account that most of the sea level rise due to the emission of greenhouse gases in the next 100 years will occur decades and centuries later. Sea level is projected to rise 0.2–0.6 meters by the year 2100, primarily as a result of thermal expansion of the oceans; however, it may eventually reach values up to several meters higher than today when the disintegration of glaciers and ice sheets contributes more strongly to sea level rise. (A sea level rise of 4 meters would submerge much of southern Florida.)

While there are uncertainties in climate projections, it is important to realize that the climate projections are based on sound scientific principles, such as the laws of thermodynamics and radiative transfer, with measurements of optical properties of gases. The record of past climate changes that can be inferred, for example, with geochemical methods from ice cores and ocean sediment cores, provides tantalizing hints of large climate changes that occurred over Earth's history, and it poses challenges to our understanding of climate (for example, there is no complete and commonly accepted explanation for the cycle of ice ages and warm periods). However, climate models are not empirical, based on correlations in such records, but incorporate our best understanding of the physical, chemical, and biological processes being modeled. Hence, evidence that temperature changes precede changes in carbon dioxide concentrations in some climate changes on the timescales of ice ages, for example, only shows that temperature changes can affect the atmospheric carbon dioxide concentrations, which in turn feed back on temperature changes. Such evidence does not invalidate the laws of thermodynamics and radiative transfer, or the conclusion that the increase in greenhouse gas concentrations in the past decades is human induced.