

THE CAUSES OF GLOBAL CLIMATE CHANGE

SCIENCE BRIEF 1

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During the twentieth century, the earth's surface warmed by about 1.4 °F. There are a variety of potential causes for global climate change, including both natural and human-induced mechanisms. Science has made great strides recently in determining which potential causes are actually responsible for the climate change that occurred during the twentieth century, providing strong evidence that greenhouse gases released to the atmosphere by human activities are the main cause of contemporary global warming.

Recent decades have seen record-high average global surface temperatures. Thermometer readings sufficient to provide reliable global averages are available back to 1850 (Brohan et al. 2006). In the past century, global surface temperature increased by about 1.4 °F (Fig. 1). In the past quarter-century, according to satellite measurements, the lower atmosphere warmed by 0.22–0.34 °F per decade, equivalent to 2–3 °F per century (Christy and Spencer 2005; Mears and Wentz 2005). The past 20 years include the 18 warmest years on record (Hadley Centre 2005).

This well-documented warming trend could result from several

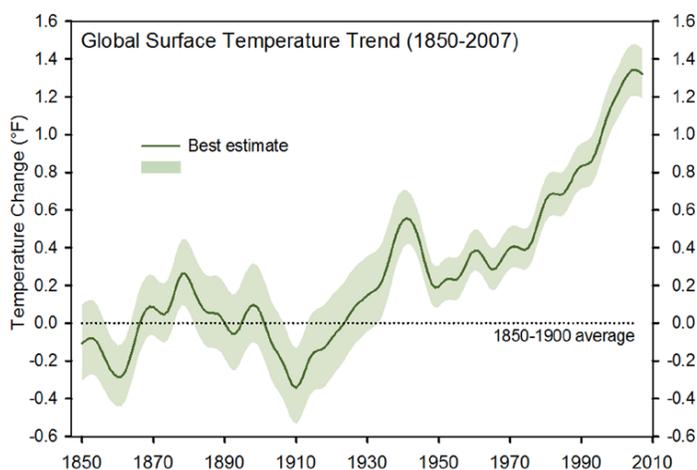


Figure 1. Average global surface temperature based on instrumental measurements (Adapted from Brohan et al. 2006; © Crown copyright 2006, data supplied by the Met Office). Temperature rise during the twentieth century is much larger than the uncertainty range.

factors that influence the earth's climate, some of which are natural, such as changes in solar radiation and volcanic activity. Others, particularly the release of certain gases to the atmosphere and land-cover changes, are man made. This brief describes recent scientific progress in identifying the causes.

The **greenhouse effect** is a natural phenomenon whereby certain gases in the earth's atmosphere, known as **greenhouse gases**, absorb heat that would otherwise escape to space. This heat originates from visible sunlight that warms the earth's surface. Subsequently, heat radiates from the surface to the atmosphere, where some of it is absorbed by greenhouse gases

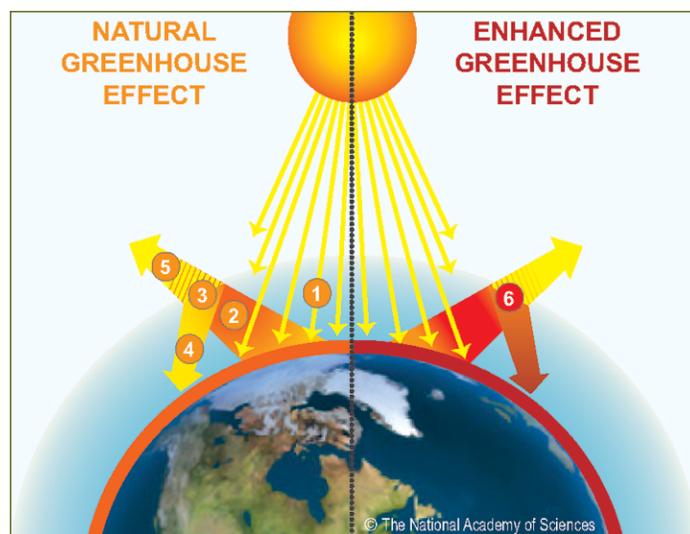


Figure 2. Illustration of the greenhouse effect (Courtesy of the Marian Koshland Science Museum of the National Academy of Sciences). Visible sunlight passes through the atmosphere without being absorbed. Some of the sunlight striking the earth is (1) absorbed and converted to infrared radiation (heat), which warms the surface. The surface (2) emits infrared radiation to the atmosphere, where some of it (3) is absorbed by greenhouse gases and (4) re-emitted toward the surface; some of the infrared radiation is not trapped by greenhouse gases and (5) escapes into space. Human activities that emit additional greenhouse gases to the atmosphere (6) increase the amount of infrared radiation that gets absorbed before escaping to space, thus enhancing the greenhouse effect and amplifying the warming of the earth.

and radiated back to the surface (Fig. 2). Recent progress in climate modeling has generated a consensus among climate scientists that greenhouse gases emitted by human activities are likely (66–90% chance) to have caused most of the observed global temperature rise over the past 50 years (Mitchell et al. 2001). The increase in the strength of the greenhouse effect as a result of man-made greenhouse gases is known as the **enhanced greenhouse effect**.

Factors that Influence Global Temperature

Global climate varies over time in response to **climate forcings**—physical factors external to the climate system that force a net increase (positive forcing) or net decrease (negative forcing) of heat in the climate system as a whole (Hansen, Sato et al. 2005). This type of change is distinct from **internal climate variability**, in which heat is transported by winds or ocean currents between different components of the climate system with no net change in the total heat within the system. The El Niño–Southern Oscillation is a well-known example of internal climate variability. Because the observed climate change over the twentieth century results from a net increase of heat in the entire climate system, it can only be explained by external forcing (Hansen, Nazarenko et al. 2005). Hence, the task for climate change scientists is to identify one or more external forcing(s)—natural or man made—that can explain the observed warming.

Until recent centuries, climate forcings were exclusively natural, such as changes in the amount of sunlight reaching the earth’s surface and changes in emissions of dust from volcanoes. During modern times, human activities have introduced a mix of additional forcings, such as increases in atmospheric greenhouse gases that cause warming (positive forcing), and **sulfate aerosols**, miniscule particles that reflect sunlight and cause cooling (negative forcing). The histories and magnitudes of various forcings are estimated from direct observations, such as satellite measurements of solar radiation in recent decades, or from proxies, such as sunspots for solar radiation in earlier decades (Foukal et al. 2004). The histories of individual forcings (Fig. 3) are then examined for the potential to cause the observed pattern of climate change (Hansen, Sato et al. 2005).

Scientists employ records of various forcings in a **fingerprinting** approach to identify which forcings can account for observed patterns of climate change (e.g., Santer et al. 2004). A particular forcing imprints itself uniquely on the past climate record based on how the forcing works and how its strength varies through space and time (e.g., Santer et al. 2004; Barnett et al. 2005). For example, volcanic eruptions cause short-term, sudden cooling. Changes in solar radiation cause warming of the lower and upper atmosphere, and follow the 11-year cycle of solar variability. Changes in greenhouse gases cause greater warming over land than oceans and warm the lower atmosphere but cool the upper atmosphere. Sulfate aerosols cause cooling that is strongest over industrialized regions. These idiosyncrasies of particular external forcings allow scientists to detect the **fingerprints** of particular forcings in records of observed climate change.

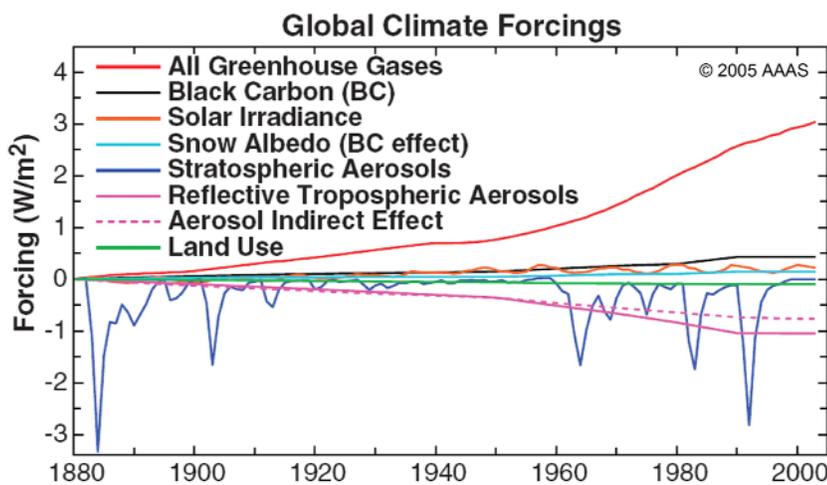


Figure 3. Forcings used to drive global climate simulations (From Hansen, Sato et al. 2005; Reprinted with permission from AAAS). Records of forcing history are compiled from a wide variety of direct observations and proxies. Each forcing has a unique historical pattern that serves as its fingerprint of influence on observed climate change. Positive forcings exert a net warming effect (e.g., greenhouse gases, red line), whereas negative forcings exert a net cooling effect (e.g., stratospheric aerosols from volcanic eruptions, dark blue line). Greenhouse gases exhibit the largest trend of all forcings shown.

Modeling to Identify Causes of Climate Change

Fingerprint matching between climate forcings and observed climate change is performed using physical climate models that calculate how each forcing should have affected climate over time, based on its history and how scientists understand the physical mechanisms of each forcing. These models are able to reproduce most of the major features of the global climate system, including the pattern of global warming over the past century (e.g., Stott et al. 2000).

The models serve as controlled experiments that test alternative hypotheses about the causes of

climate change. Each forcing depicted in Fig. 3 represents a hypothesized cause of observed climate change. Entering records of one or more forcings into a model, scientists assess whether the climate scenario generated by the model is similar to the observed climate record; no observed climate data are entered into the model. If the simulated climate matches observed climate, then the forcing(s) represented in the model can explain the observed climate record. If not, the forcing(s) cannot explain the observed climate change. Of course, it is possible that more than one forcing is involved, so scientists test all possible combinations of forcings to see if their combined influence can explain observed climate change (e.g., Meehl et al. 2004).

Independent modeling of different components of the climate system demonstrates that man-made greenhouse gases have been the dominant forcing of climate change over the past half-century. The distinct fingerprint of man-made greenhouse gases has been detected in records of surface temperature, ocean heat content, and the vertical structure of the atmosphere above the earth's surface.

Surface warming. The twentieth-century warming trend at the earth's surface progressed in a distinct pattern, with a large warming during 1910-1940, moderate cooling during 1940-1975, and a large warming from 1975 to the present (Fig. 1). Scientists at the National Center for Atmospheric Research (NCAR) looked for fingerprints of various natural (solar radiation, volcanic particles) and man-made (greenhouse gases, sulfate aerosols) forcings in this record of observed climate change (Meehl et al. 2004). The study employed a physical climate model that allowed individual or combinations of forcings to drive the simulated climate. The change in surface temperature calculated by the model for each forcing or combination of forcings was then compared with the observed record of surface temperature change over the twentieth century (Fig. 4).

The best fit of the model results to the observed climate was produced when all of the forcings were included, implicating all of the forcings in producing the overall pattern of change (Fig. 4A). However, different forcings dominated at different times during the century (Takemura et al. 2006). For instance, the temperature rise in the early part of the century was dominated by natural forcings (Fig. 4B), whereas the warming after 1975 was dominated by man-made greenhouse gases (Fig. 4C). The cooling during the mid-century was consistent with a combination of natural volcanic and man-made aerosols (Nagashima et al. 2006).

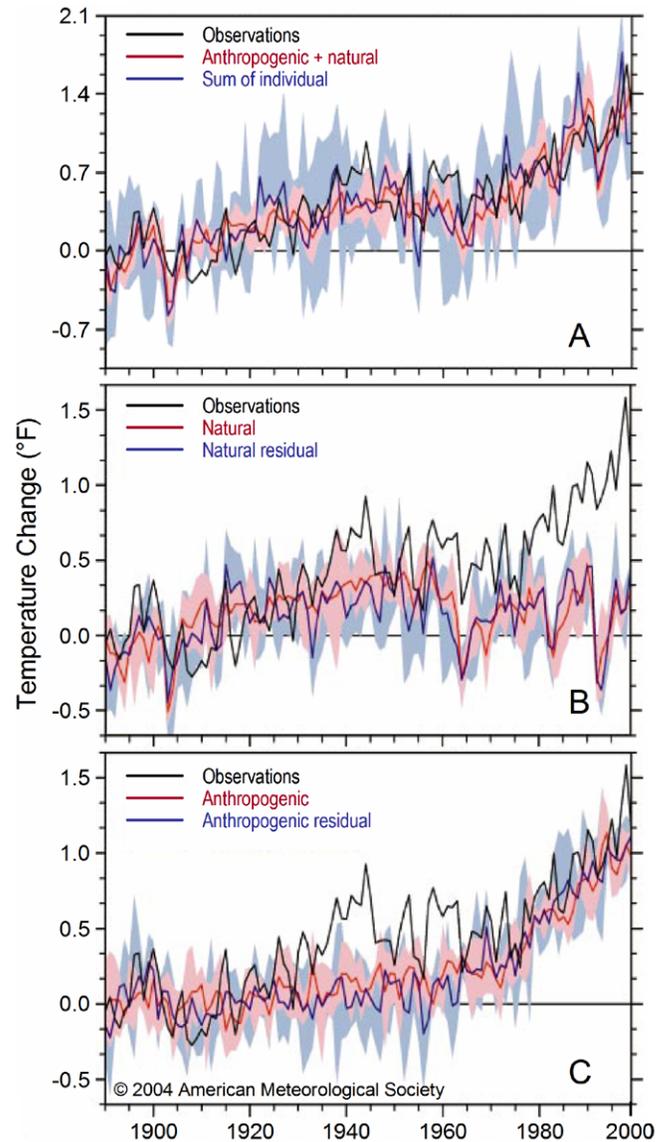


Figure 4. Fingerprint-modeling of global surface temperature change (Adapted from Meehl et al. 2004). (A) Model results with all forcings included. The combined forcings provided the best match to the fingerprint of climate change in the observed record. (B) Natural forcings alone explained much of the temperature change in the first half of the century. (C) Man-made forcings strongly dominated the temperature change after 1975.

The results of this study implicate the enhanced greenhouse effect as the dominant cause of global warming over the past three decades. If not for the temporary cooling between 1940 and 1975 from volcanic and man-made aerosol emissions, the earth might be even warmer than it is today (Mitchell et al. 2001).

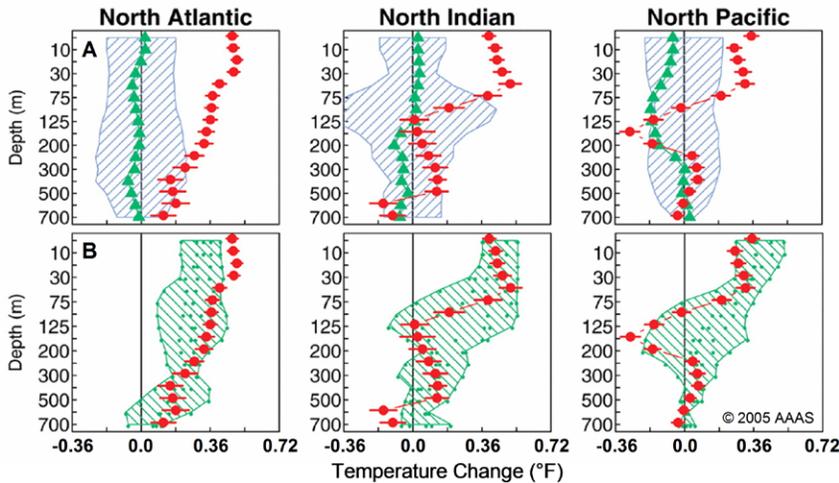


Figure 5. Observed and simulated heat penetration into three ocean basins (Adapted from Barnett et al. 2005; Reprinted with permission from AAAS). (A) The blue hatched region represents the 90% confidence limits of modeled natural internal variability resulting from heat exchange among different ocean basins. The observed record of temperature change (red dots) bears little resemblance to that expected from internal variability. The strength of the warming trend forced by observed solar and volcanic variability (green triangles) shows little agreement with the observed climate trend. (B) The modeled human-induced forcing from greenhouse gases and sulfate aerosols (green hatched region) shows substantial fingerprint matching with the observed heat penetration (red dots).

Ocean heat content. Oceans exhibit natural temperature cycles, with some oceans cooling at the same time that others warm. This natural **internal variability** of climate results from heat transport from one place to another, but it adds no new heat to the ocean as a whole. A major challenge for assigning a cause to temperature changes is distinguishing internal variability from external forcing, which adds new heat to the system. Recently, scientists from the U.S. National Oceanographic and Atmospheric Administration demonstrated that the ocean as a whole has been warming for the past five decades (Levitus et al. 2005). The first principles of physics dictate that simultaneous warming of all the world's oceans could only occur through external forcing, as there is no other source of this much energy within the climate system (Hansen, Nazarenko et al. 2005).

Using a fingerprinting-modeling approach similar to the one described above, scientists at Scripps Institution of Oceanography, Lawrence Livermore National Lab, NCAR, and the United Kingdom's Hadley Center, published a study showing that the oceans situated along the equator have warmed over the past five decades as a direct result of the enhanced greenhouse effect (Barnett et al. 2005).

Observations show that the oceans have been warming from the surface downward (red dots, Fig. 5), which indicates heat transfer from the atmosphere. The vertical pattern of heat penetration with depth varies from ocean to ocean as a result of internal variability (i.e. currents transporting heat from one ocean to another). This complex pattern of vertical profiles provides a “fingerprint” of climate forcing. Modeling of internal variability alone or internal variability combined with solar and volcanic forcings did not produce temperature profiles that matched this fingerprint (Fig. 5A). However, the combined influence of human-induced forcings, natural forcings, and internal variability reproduced the pattern of heat penetration for each ocean (Fig. 5B). Man-made greenhouse gases strongly dominated the overall forcing.

Vertical structure of the atmosphere. Another fingerprint of the enhanced greenhouse effect has been identified in the observed increase in the height of the **tropopause**, a region of the earth's atmosphere that represents the transition between the lower atmosphere (troposphere) and the upper atmosphere (stratosphere). Factors that either warm the troposphere or cool the stratosphere increase the tropopause elevation (Fig. 6), and

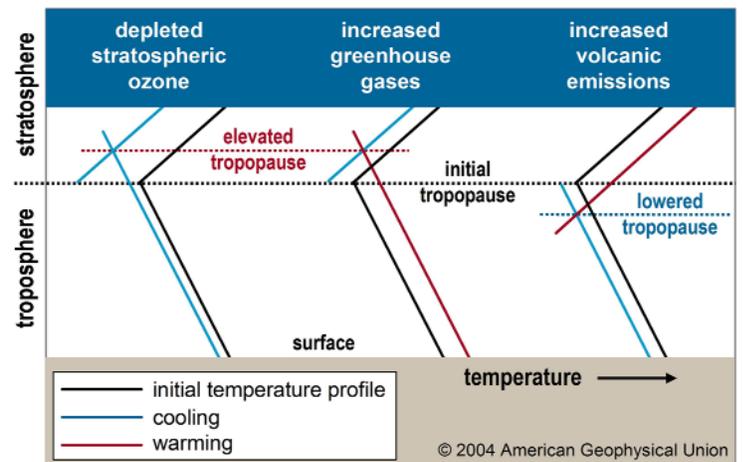


Figure 6. Conceptual model for the effects of three different forcings on tropopause height (Adapted from Santer et al. 2004). The solid black lines are the baseline atmospheric temperature profiles. Forcing by either stratospheric ozone depletion or increases in well-mixed atmospheric greenhouse gases increase tropopause height; volcanic forcing decreases tropopause height.

climate models have long predicted that the elevation of the tropopause above the earth's surface should increase as a result of the enhanced greenhouse effect (Santer et al. 2003). Although this phenomenon may affect climate behavior, it is discussed here strictly as a tool for identifying causes of observed climate change.

Scientists from several American, British, and German research institutions employed a fingerprinting-modeling approach to determine which climate forcings could explain observed changes in the height of the tropopause (Santer et al. 2003; Santer et al. 2004). Between 1979 and 2001, satellites monitoring the atmosphere recorded a 620-foot rise of the tropopause. In the model simulations forced by both natural and human-induced forcings, the tropopause elevation increased similarly (Fig. 7A). Man-made greenhouse gases, which warmed the troposphere, and stratospheric ozone depletion (by man-made chemicals), which cooled the stratosphere, dominated the forcing. Man-made greenhouse gases caused about 40 percent of the rise (Fig. 7B, green line), whereas ozone depletion caused about 60 percent (Fig. 7B, purple line). Overall, the effect of solar forcing, which contributed slightly (less than 10%) to the rise of the tropopause, was canceled by a small negative forcing (decrease in tropopause height) from volcanoes (Fig. 7B, gray line; note the transitory decreases corresponding to the eruptions of the Agung, El Chichón, and Pinatubo volcanoes). Thus, human-induced forcings from greenhouse gases and ozone-depleting chemicals provide the best explanation for the observed increase in the elevation of the tropopause over the past few decades.

Summary

Scientific understanding of the causes of climate change has progressed dramatically in the past few years. Natural internal variability is an inherent feature of the climate system, but it cannot account for the net gain of energy that has been detected within the climate system as a whole. Based on physical principles, the modern increase in the heat content of the global ocean demonstrates that positive external forcing of the climate is underway. Changes in natural external forcings cannot explain the observed global warming of recent decades.

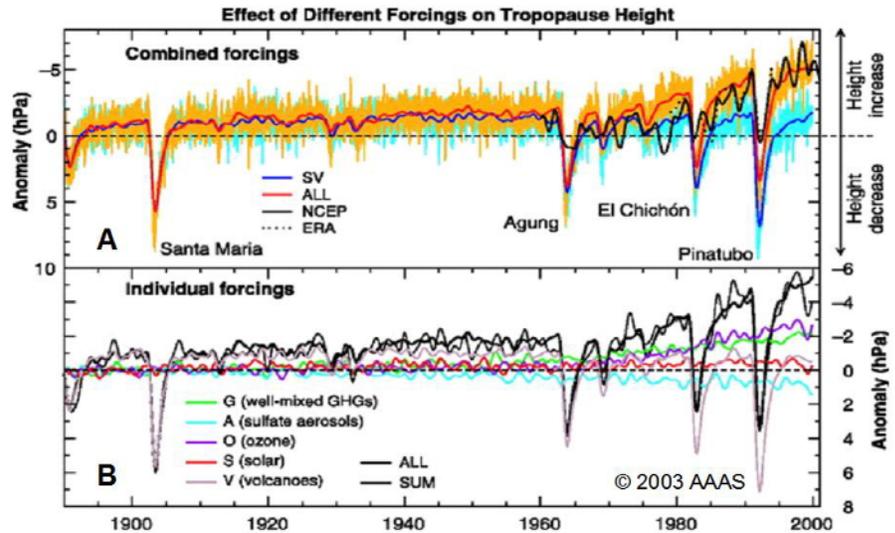


Figure 7. Global average change in tropopause height (From Santer et al. 2003; Reprinted with permission from AAAS). (A) Observations (NCEP and ERA) and model results driven by combined solar and volcanic forcing (SV) or combined natural and human-induced forcings (ALL). (B) Change in global average tropopause height according to model results driven by individual forcings as compared to combined forcings (ALL and SUM). "ALL" refers to a single model realization with all forcings included. "SUM" refers to the sum of separate model realizations for individual forcings. Good agreement between ALL and SUM indicates that the influences of the different forcings are additive.

Records of observed climate change at the earth's surface, in the global ocean, and in the atmosphere, bear the fingerprint of the enhanced greenhouse effect, which is caused by human activities associated with fossil fuel burning and land use. Recent progress in understanding this scientific framework led the 2007 assessment report of the Intergovernmental Panel on Climate Change to conclude:

Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely [i.e. greater than 90% certainty] due to the observed increase in anthropogenic greenhouse gas concentrations. This is an advance since the [2001 IPCC report] conclusion that "most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations".

Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns. (IPCC 2007)

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