PERSPECTIVES: CLIMATE CHANGE

The Causes of 20th Century Warming

Francis W. Zwiers and Andrew J. Weaver

Since 1860, global mean surface air temperatures have increased by 0.6 ±0.2°C, but this warming has not been continuous (*1*). Most of the warming has occurred during two distinct periods, from 1910 to 1945 and since 1976, with a very gradual cooling during the intervening period. Global warming critics have been quick to point out that the warming in the early 20th century occurred before the buildup of atmospheric greenhouse gases and have also noted that most model simulations of 20th century climate have failed to capture this feature. Recent studies (*2–4*) have suggested that natural factors such as solar variability and lack of volcanic activity may have been important factors in the early warming.

Stott *et al.* have undertaken a study with a state-of-the-art climate model to investigate systematically the relative effects of natural and anthropogenic forcing on the climate of the 20th century. (A forcing is the energy imbalance caused by changes such as rising greenhouse gas concentrations; a net positive forcing will cause a warming.) On page 2133 of this issue (*5*), they report the most comprehensive simulation of 20th century climate to date. They find that natural forcing alone cannot account for the warming in recent decades. Similarly, anthropogenic forcing alone is insufficient to explain the warming from 1910 to 1945 but necessary to reproduce the warming since 1976.

Stott *et al.*'s simulations are based on estimated historical variations in the main anthropogenic and natural external forcings (see the sketch on this page) that are believed to have affected the climate of the past century. The anthropogenic forcings include heat-trapping greenhouse gases, changes in ozone abundance (also a greenhouse gas), and sulfate aerosols from the industrial emission of sulfur dioxide. These aerosols cool global climate by scattering incoming sunlight back to space and by altering the reflectivity and lifetime of clouds. The emission and concentration history of greenhouse gases and the resulting forcing are relatively well known, as is the (substantially smaller) forcing from changes in the ozone distribution. Historical sulfur dioxide emissions can be derived relatively accurately from records of fossil fuel production, but the total amount of sulfate aerosol formed and the magnitude of its climatic effects remain uncertain. Indeed, Stott *et al.* note that their model, which includes the processes that create, transport, and remove sulfate aerosols, produces only about half of the observed aerosol concentrations over Europe. Forcing by other types of aerosols, such as mineral dust, aerosols from biomass burning, and industrially emitted black carbon, is uncertain but believed to be small and is not included in the Stott *et al.* simulations.

The magnitude of natural climate forcings is also relatively uncertain. Instrumental observations of variations in solar irradiance are available only for the last two solar cycles (about 22 years), and estimates of solar forcing must therefore rely on reconstructions from proxy sources (*6*). Reconstructions of solar irradiance differ widely but agree that the forcing is positive over the 20th century and that it has increased by around 10 to 20% of the change in greenhouse gas forcing. Reconstructions of volcanic forcing (*7*) are similarly uncertain because instrumental observations of stratospheric aerosol loading are only available for the past two decades and they must therefore rely on phenomenological and proxy observations before that time. Different reconstructions disagree on the size and timing of individual events but agree on the general patterns of volcanic activity on decadal and longer time scales, such as the interruption in volcanic activity between about 1920 and 1960 and its resumption during the last three decades of the 20th century.

Stott *et al.* have performed a comprehensive suite of climate simulations with these forcings. Simulations incorporating only anthropogenic forcings reproduce the warming of the last three decades well but underestimate the early 20th century warming and do not capture the slight cooling between the two periods of rapid warming. This in itself is not new: Many groups around the world have observed a similar response in their model simulations. What is novel are the sets of simulations that consider only natural forcing and combined anthropogenic plus natural forcing. The natural forcing simulations produce a gradual warming up to about 1960, followed by a return to late 19th century temperatures. This is consistent with the gradual change in solar forcing throughout the 20th century and the resumption of volcanic activity during the past few decades. Only the combined forcing simulations are able to reproduce much of the observed decadal scale variation in global mean temperature for the entire 20th century (see the graph on the next page). Furthermore, they capture with some fidelity the large-scale spatial structure of the observed changes.

By relating the large-scale climate signals from their forced simula-

Climate forcing processes included in Stott *et al.*'s simulations. The climate system is driven by solar irradiation. The solar energy that enters the atmosphere must pass through the stratosphere, into which volcanic activity irregularly injects sulfate aerosols. When present, these aerosols scatter a portion of the incoming solar radiation back to space. Solar radiation that penetrates the stratosphere may be reflected back to space by clouds or aerosols in the troposphere. Solar radiation that reaches the land surface is reflected back into the atmosphere or converted to latent heat (through evaporation and transpiration) or sensible heat (infrared radiation). The so-called greenhouse gases, including water vapor, carbon dioxide, methane, and chlorofluorocarbons (CFCs), transfer infrared radiation less efficiently than other gases, thereby trapping this energy in the troposphere. Increased concentrations of these gases therefore cause a positive radiative forcing (warming) of the climate.

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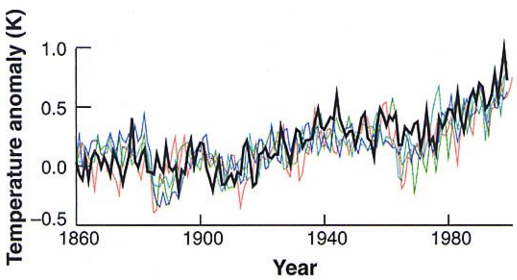
tions to decadal mean observations, Stott *et al.* demonstrate that natural forcing alone is not a plausible explanation for the observed changes in the 20th century and that natural and anthropogenic forcing have both made substantial contributions to the observed change. Together, these forcings explain about 80% of the observed interdecadal variance of global mean temperature.

The result is compelling, but more work is needed. There is still much uncertainty on the mechanism and magnitude of aerosol forcing and on feedback mechanisms involving clouds, the ocean, cryosphere, and the land surface. Historical reconstructions of natural climate forcing also remain uncertain. And the ability of models to simulate the variability of the climate system must be improved. For example, Stott *et al.* point out that their forced simulations do not reproduce the observed trend in the North Atlantic Oscillation (*8*). Also, most models do not accurately simulate the El Niño–Southern Oscillation in the Pacific (*9*).

Nevertheless, this impressive study is a substantial step toward explaining the observed variations of 20th century climate. Stott *et al.*'s approach is far from a diagnostic curve fitting exercise. Rather, a model built on physical principles is used to simulate the climatic response to independent estimates of historical climate forcing. The agreement between observed and simulated decadal-scale temperature variations strongly supports the contention that forcing from anthropogenic activities, moderated by variations in solar and volcanic forcing, has been the main driver of climate change during the past century.



A good match. 20th century global mean surface air temperature departures from the 1880–1920 average. Observations are shown in black; simulations by Stott *et al.* (*5*) are shown in color. The simulations include natural and anthropogenic forcing. Further details in (*5*).

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References and Notes

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7. Stott *et al.* used the reconstruction by M. Sato, J. E. Hansen, M. P. McCormick, and J. Pollack [*J. Geophys. Res.* **98**, 22987 (1993)]. For another volcanic aerosol forcing reconstruction that has been used in climate simulations, see A. Robock and M. P. Free [in *Climatic Variations and Forcing Mechanisms of the Last 2000 Years*, P. Jones, R. Bradley, J. Jouzel, Eds. (Springer-Verlag, Berlin, 1996), pp. 533–546.]
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PERSPECTIVES: PARTICLE PHYSICS

How Strange Is the Proton?

Günther Rosner

Nucleons (protons and neutrons) have been extensively studied over the past 30 or 40 years, but our knowledge of their internal structure is still rather limited. We do not even know exactly what they are made of. Do they consist of only light quarks or do heavy quarks, such as "strange" quarks, contribute as well? The main reason for these difficulties is that the nucleon cannot be taken apart because its constituents, the quarks, are extremely tightly bound. If one tries to remove a quark, it immediately combines with an antiquark in the surrounding vacuum to become a meson (a composite particle containing one quark and one antiquark). The only way to look inside the nucleons is through scattering experiments and the measurement of "form factors" (*1*), which carry information about the spatial distribution of charges, spins and currents within the nucleon. As reported by Hasty *et al.* on page 2117 of this issue (*2*), these measurements are also helping to determine the role of "strange" quarks, originally thought not to play a role in ordinary matter.

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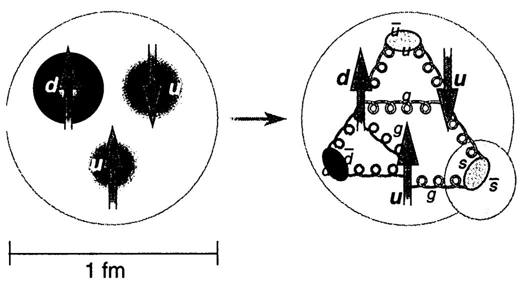
In the 1960s, it became clear that neutrons and protons are not elementary but are composite particles. Symmetry considerations initially led to the simple idea that nucleons consist of three, either up (*u*) or down (*d*), quarks (see the left part of the figure). The quarks are confined within the nucleon, each carrying one-third of its mass of about 939 MeV/c^2. They have spins of $^1/_2$, which combine to give a total spin of $^1/_2$ for the nucleon.



Artist's view of a proton. (Left) In the static quark model, massive constituent *u* and *d* quarks are confined to the proton's volume (the proton has a diameter of about 1 fm = 10^{-15} m). **(Right)** In the QCD picture of the proton, the *u* and *d* quarks are light and pointlike. The proton's volume is filled by gluons (*g*) and quark-antiquark pairs. The figure is based on a template by Frank Maas, University of Mainz.

This model was soon found to be too simplistic. Electron scattering experiments in the 1970s showed that the quarks carry only about half of the proton's momentum. The rest is carried by particles called gluons, which are exchanged between the quarks and produce the extremely strong forces that hold the proton together. According to the theory of strong interactions, quantum chromodynamics (QCD), the *u* and *d* quarks still carry a spin of $^1/_2$ but are now pointlike and have masses of only 5 to 10 MeV/c^2. The gluons can temporarily split into quark-antiquark pairs (see the right part of the figure). These "sea-quark" pairs may be formed by *u* or *d* quarks and their respective antiquarks or by the strange quark (*s*) and its antiquark. The strange quark has a mass of around 150 MeV/c^2 and is thus much heavier than the *u* and *d* quarks. It is not yet known to what extent strange quarks determine the nucleon's properties, and this is what Hasty *et al.* and other groups are aiming to resolve.

Two earlier sets of experiments have investigated "strangeness" in the nucleon using lepton or pion beams. (Leptons, such as the electron and the heavier muon, are the lightest elementary particles. Pions are the lightest mesons.) First, analyses of pion-nucleon scattering data in the 1970s (*3*, *4*) indicated that strange quarks might contribute considerably to the nucleon's mass. The strange quark content of the

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