Testimony for House Committee on Science and Technology Subcommittee on Energy and Environment

Hearing on “A Rational Discussion of Climate Change: The Science, the Evidence, the Response”

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1. Biographical information

My name is Benjamin Santer. I am a climate scientist. I work at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory (LLNL) in California. I am testifying today as a member of Lawrence Livermore National Laboratory and of PCMDI.

I have been employed at PCMDI since 1992. PCMDI was established in 1989 by the U.S. Department of Energy, and has been at LLNL since then. PCMDI's mission is to quantify how well computer models simulate important aspects of present-day and historical climate, and to reduce uncertainties in model projections of future climate change.

PCMDI is not engaged in developing its own computer model of the climate system ("climate model"). Instead, we study the performance of all the world's major climate models. We also coordinate international climate modeling simulations, and help the entire climate science community to analyze and evaluate climate models.

I have a Ph.D. in Climatology from the Climatic Research Unit of the University of East Anglia in the United Kingdom. I went to the Climatic Research Unit in 1983 because it was (and still is) one of the world's premier institutions for studying past, present, and future climate. During the course of my Ph.D., I was privileged to work together with exceptional scientists – with people like Tom Wigley, Phil Jones, Keith Briffa, and Sarah Raper.

My thesis explored the use of so-called "Monte Carlo" methods in assessing the quality of different climate models. After completing my Ph.D. in 1987, I spent five years at the Max-Planck Institute for Meteorology in Hamburg, Germany. During my time in Hamburg, I worked with Professor Klaus Hasselmann on the development and application of "fingerprint" methods, which are valuable tools for improving our understanding of the nature and causes of climate change.

Much of the following testimony is adapted from a chapter Tom Wigley and I recently published in a book edited by the late Professor Stephen Schneider (1), and from previous testimony I gave to the House Select Committee on Energy Independence and Global Warming (2).

2. Introduction

In 1988, the Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization and the United Nations Environment Programme. The goals of this panel were threefold: to assess available scientific information on climate change, to evaluate the environmental and societal impacts of climate change, and to formulate response strategies. The IPCC's first major scientific assessment, published in 1990, concluded that "unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more" (3).

In 1996, the IPCC's second scientific assessment made a more definitive statement regarding human impacts on climate, and concluded that "the balance of evidence suggests a discernible human influence on global climate" (4). This cautious sentence marked a paradigm shift in our scientific understanding of the causes of recent climate change. The shift arose for a variety of reasons. Chief amongst these was the realization that the cooling effects of sulfate aerosol particles (which are produced by burning fossil fuels that contain sulfates) had partially masked the warming signal arising from increasing atmospheric concentrations of greenhouse gases (5).

A further major area of progress was the increasing use of "fingerprint" studies (6, 7, 8). The strategy in this type of research is to search for a "fingerprint" (the climate change pattern predicted by a computer model) in observed climate records. The underlying assumption in fingerprinting is that each "forcing" of climate – such as changes in the Sun's energy output, volcanic dust, sulfate aerosols, or greenhouse gas concentrations – has a unique pattern of climate response (see Figure 1). Fingerprint studies apply signal processing techniques very similar to those used in electrical engineering (6). They allow researchers to make rigorous tests of competing hypotheses regarding the causes of recent climate change.

The third IPCC assessment was published in 2001, and went one step further than its predecessor. The third assessment reported on the magnitude of the human effect on climate. It found that "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" (9). This conclusion was based on improved estimates of natural climate variability, better reconstructions of temperature fluctuations over the last millennium, continued warming of the climate system, refinements in fingerprint methods, and the use of results from more (and improved) climate models, driven by more accurate and complete estimates of the human and natural "forcings" of climate.

This gradual strengthening of scientific confidence in the reality of human influences on global climate continued in the IPCC AR4 report, which stated that "warming of the climate system is unequivocal", and that "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" (10) (where "very likely" signified >90% probability that the statement is correct). The AR4 report justified this increase in scientific confidence on the basis of "…longer and improved records, an expanded range of observations and improvements in the simulation of many aspects of climate and its variability" (10). In its contribution to the AR4, IPCC Working Group II concluded that anthropogenic warming has had a discernible influence not only on the physical climate system, but also on a wide range of biological systems which respond to climate (11).

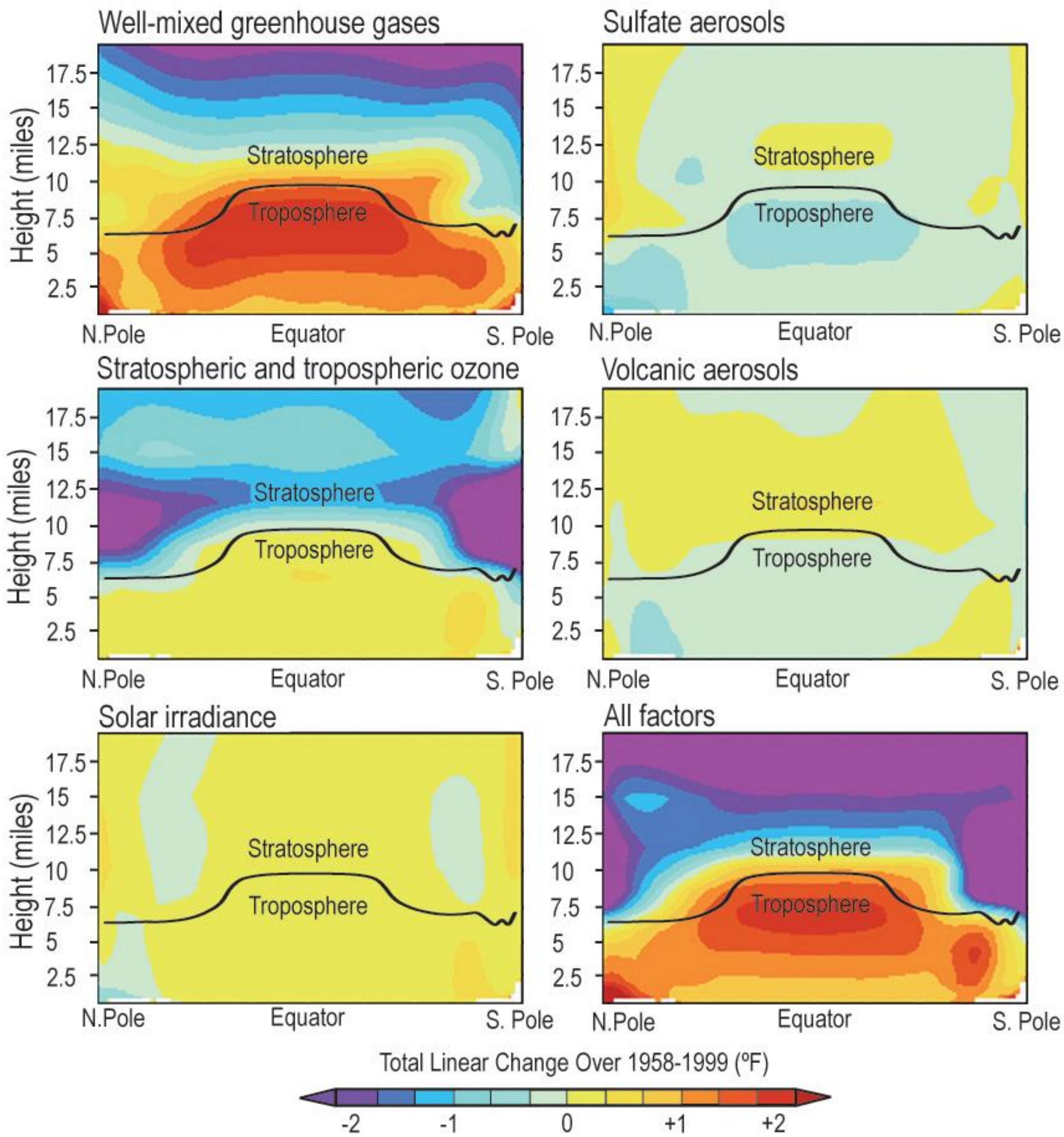

Figure 1: Climate simulations of the vertical profile of temperature change due to five different factors, and the effect due to all factors taken together. The panels above represent a cross-section of the atmosphere from the North Pole to the South Pole, and from the surface up into the stratosphere. The black lines show the approximate location of the tropopause, the boundary between the lower atmosphere (the troposphere) and the stratosphere. This Figure is reproduced from Karl *et al*. (12).

Extraordinary claims require extraordinary proof (13). The IPCC's extraordinary claim that human activities significantly altered both the chemical composition of Earth's atmosphere and the climate system has received extraordinary scrutiny. This claim has been independently corroborated by the U.S. National Academy of Sciences (14), the Science Academies of eleven nations (15), and the Synthesis and Assessment Products of the U.S. Climate Change Science Plan (16). Many of our professional scientific organizations have also affirmed the reality of a human influence on global climate (17).

Despite the overwhelming evidence of pronounced anthropogenic effects on climate, important uncertainties remain in our ability to quantify the human influence. The experiment that we are performing with the Earth's atmosphere lacks a suitable control: we do not have a convenient "undisturbed Earth", which would provide a reference against which we could measure the anthropogenic contribution to climate change. We must therefore rely on numerical models and paleoclimate evidence (18, 19, 20) to estimate how the Earth's climate might have evolved in the absence of any human intervention. Such sources of information will always have significant uncertainties.

In the following testimony, I provide a personal perspective on recent developments in the field of detection and attribution ("D&A") research. Such research is directed towards detecting significant climate change, and then attributing some portion of the detected change to a specific cause or causes (21, 22, 23, 24). I also make some brief remarks about openness and data sharing in the climate modeling community, and accommodation of "alternative" views in the IPCC.

3. Recent Progress in Detection and Attribution Research

Fingerprinting

The IPCC and National Academy findings that human activities are affecting global-scale climate are based on multiple lines of evidence:

1. Our continually-improving physical understanding of the climate system, and of the human and natural factors that cause climate to change;
2. Evidence from paleoclimate reconstructions, which enables us to place the warming of the 20th century in a longer-term context (25, 26);
3. The qualitative consistency between observed changes in different aspects of the climate system and model predictions of the changes that should be occurring in response to human influences (10, 27);

4. Evidence from rigorous quantitative fingerprint studies, which compare observed patterns of climate change with results from computer model simulations.

Most of my testimony will focus on the fingerprint evidence, since this is within my own area of scientific expertise.

As noted above, fingerprint studies search for some pattern of climate change (the "fingerprint") in observational data. The fingerprint can be estimated in different ways, but is typically obtained from a computer model experiment in which one or more human factors are varied according to the best-available estimates of their historical changes. Different statistical techniques are then applied to quantify the level of agreement between the fingerprint and observations and between the fingerprint and estimates of the natural internal variability of climate. This enables researchers to make rigorous tests of competing hypotheses (28) regarding the possible causes of recent climate change (21, 22, 23, 24).

While early fingerprint work dealt almost exclusively with changes in near-surface or atmospheric temperature, more recent studies have applied fingerprint methods to a range of different variables, such as changes in ocean heat content (29, 30), Atlantic salinity (31), sea-level pressure (32), tropopause height (33), rainfall patterns (34, 35), surface humidity (36), atmospheric moisture (37, 38), continental river runoff (39), and Arctic sea ice extent (40). The general conclusion is that for each of these variables, natural causes alone cannot explain the observed climate changes over the second half of the 20th century. The best statistical explanation of the observed climate changes invariably involves a large human contribution.

These fingerprint results are robust to the processing choices made by different groups, and show a high level of physical consistency across different climate variables. For example, observed atmospheric water vapor increases (41) are physically consistent with increases in ocean heat content (42, 43) and near-surface temperature (44, 45).

There are a number of popular misconceptions about fingerprint evidence. One misconception is that fingerprint studies consider global-mean temperatures only, and thus provide a very poor constraint on the relative contributions of human and natural factors to observed changes (46). In fact, fingerprint studies rely on information about the detailed spatial structure (and often the combined space and time structure) of observed and simulated climate changes. Complex patterns provide much stronger constraints on the possible contributions of different factors to observed climate changes (47, 48, 49).

Another misconception is that computer model estimates of natural internal climate variability ("climate noise") are accepted uncritically in fingerprint studies, and are never tested against observations (50). This is demonstrably untrue. Many fingerprint studies test whether model estimates of climate noise are realistic. Such tests are routinely performed on year-to-year and decade-to-decade timescales, where observational data are of sufficient length to obtain reliable estimates of observed climate variability (51, 52, 53, 54).

Because regional-scale climate changes will determine societal impacts, fingerprint studies are increasingly shifting their focus from global to regional scales (55). Such regional studies face a number of challenges. One problem is that the noise of natural internal climate variability typically becomes larger when averaged over increasingly finer scales (56), so that identifying regional and local climate signals becomes more difficult.

Another problem relates to the climate “forcings” used in computer model simulations of historical climate change. As scientific attention shifts to ever smaller spatial scales, it becomes more important to obtain reliable information about these forcings. Some forcings are both uncertain and highly variable in space and time (57, 58). Examples include human-induced changes in land surface properties (59) or in the concentrations of carbon-containing aerosols (60,61). Neglect or inaccurate specification of these factors complicates D&A studies.

Despite these problems, numerous researchers have now shown that the climate signals of greenhouse gases and sulfate aerosols are identifiable at continental and sub-continental scales in many different regions around the globe (62, 63, 64, 65). Related work (66, 67) suggests that a human-caused climate signal has already emerged from the background noise at spatial scales at or below 500 km (68), and may be contributing to regional changes in the distributions of plant and animal species (69).

In summarizing this section of my testimony, I note that the focus of fingerprint research has evolved over time. Its initial emphasis was on global-scale changes in Earth’s surface temperature. Subsequent research demonstrated that human fingerprints were identifiable in many different aspects of the climate system – not in surface temperature only. We are now on the verge of detecting human effects on climate at much finer regional scales of direct relevance to policymakers, and in variables tightly linked to climate change impacts (70, 71, 72, 73, 74).

Assessing Risks of Changes in Extreme Events

We are now capable of making informed scientific statements regarding the influence of human activities on the likelihood of extreme events (75, 76, 77).

As noted previously, computer models can be used to perform the control experiment (no human effects on climate) that we cannot perform in the real world. Using the “unforced” climate variability from a multi-century control run, it is possible to determine how many times an extreme event of a given magnitude should have been observed in the absence of human interference. The probability of obtaining the same extreme event is then calculated in a perturbed climate – for example, in a model experiment with historical or future increases in greenhouse gases, or under some specified change in mean climate (78). Comparison of the frequencies of extremes in the control and perturbed experiments allows climate scientists to make probabilistic statements about how human-induced climate change may have altered the likelihood of the extreme event (53, 78, 79). This is sometimes referred to as an assessment of "fractional attributable risk" (78).

Recently, a "fractional attributable risk" study of the 2003 European summer heat wave concluded that "*there is a greater than 90% chance that over half the risk of European summer temperatures exceeding a threshold of 1.6 K is attributable to human influence on climate*" (78).

This study (and related work) illustrates that the "D&A" community has moved beyond analysis of changes in the mean state of the climate. We now apply rigorous statistical methods to the problem of estimating how human activities may alter the probability of occurrence extreme events. The demonstration of human culpability in changing these risks is likely to have significant implications for the debate on policy responses to climate change.

4. Summary of Detection and Attribution Evidence

In evaluating how well a novel has been crafted, it is important to look at the internal consistency of the plot. Critical readers examine whether the individual storylines are neatly woven together, and whether the internal logic makes sense.

We can ask similar questions about the "story" contained in observational records of climate change. The evidence from numerous sources (paleoclimate data, rigorous fingerprint studies, and qualitative comparisons of modeled and observed climate changes) shows that the climate system is telling us an internally consistent story about the causes of recent climate change.

Over the last century, we have observed large and coherent changes in many different aspects of Earth's climate. The oceans and land surface have warmed (29, 30, 42, 43, 44, 45, 80, 81). Atmospheric moisture has increased (36, 37, 38, 41). Rainfall patterns have changed (34, 35). Glaciers have retreated over most of the globe (82, 83, 84). The Greenland Ice Sheet has lost some of its mass (85). Sea level has risen (86). Snow and sea-ice extent have decreased in the Northern Hemisphere (40, 87, 88, 89). The stratosphere has cooled (90), and there are now reliable indications that the troposphere has warmed (16, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100). The height of the tropopause has increased (33). Individually, all of these changes are consistent with our scientific understanding of how the climate system should be responding to anthropogenic forcing. Collectively, this behavior is inconsistent with the changes that we would expect to occur due to natural variability alone.

There is now compelling scientific evidence that human activity has had a discernible influence on global climate. However, there are still significant uncertainties in our estimates of the size and geographical distribution of the climate changes projected to occur over the 21st century

(10). These uncertainties make it difficult for us to assess the magnitude of the mitigation and adaptation problem that faces us and our descendants. The dilemma that confronts us, as citizens and stewards of this planet, is how to act in the face of both hard scientific evidence that our actions are altering global climate and continuing uncertainty in the magnitude of the planetary warming that faces us.

5. Openness and Data Sharing in the Climate Modeling Community

Recently, concerns have been expressed about ease of access to the information produced by computer models of the climate system. "Climate modeling" is sometimes portrayed as a secretive endeavor. This is not the case.

In the 1970s and 1980s, the evaluation and intercomparison of climate models was largely a qualitative endeavor, mostly performed by modelers themselves. It often involved purely visual examination of maps from a single model and observations (or from several different models). There were no standard benchmark experiments, and there was little or no community involvement in model diagnosis. It was difficult to track changes in model performance over time (101).

This situation changed dramatically with the start of the Atmospheric Model Intercomparison Project (AMIP) in the early 1990s. AMIP involved running different Atmospheric General Circulation Models (AGCMs) with observed sea-surface temperatures and sea-ice changes over 1979 to 1988. Approximately 30 modeling groups from 10 different countries participated in the design and diagnosis of the AGCM simulations. Subsequent "revisits" of AMIP enabled the climate community to track changes in model performance over time (102).

The next major Model Intercomparison Project ("MIP") began in the mid-1990s. In phase 1 of the Coupled Model Intercomparison Project (CMIP-1), over a dozen fully-coupled Atmosphere/Ocean General Circulation Models (A/OGCMs) were used to study the response of the climate system to an idealized climate-change scenario – a 1% per year (compound interest) increase in levels of atmospheric CO_2 (103). The key aspect here was that each modeling group performed the same benchmark simulation, allowing scientists to focus their attention on the task of quantifying (and understanding) uncertainties in computer model projections of future climate change.

AMIP and CMIP have spawned literally dozens of other international Model Intercomparison Projects. "MIPs" are now a *de facto* standard in the climate science community. They have allowed climate scientists to:

- Identify systematic errors common to many different models;
- Track changes in model performance over time (in individual models and collectively);

- Make informed statements about the relative quality of different models;
- Quantify uncertainties in model projections of future climate change.

Full community involvement in "MIPs" has led to more thorough model diagnosis, and to improved climate models.

Perhaps the best-known model intercomparison is phase 3 of CMIP. The CMIP-3 project was a valuable resource for the Fourth Assessment Report (FAR) of the IPCC (10). In the course of CMIP-3, simulation output was collected from 25 different A/OGCMs. The models used in these simulations were from 17 modeling centers and 13 countries. Twelve different types of simulation were performed with each model. The simulations included so-called "climate of the 20th century" experiments (with estimated historical changes in greenhouse gases, various aerosol particles, volcanic dust, solar irradiance, *etc*.), pre-industrial control runs (with no changes in human or natural climate forcings), and scenarios of future changes in greenhouse gases. All of the simulation output was stored at LLNL's PCMDI.

At present, 35 Terabytes of CMIP-3 data are archived at PCMDI, and nearly 1 Petabyte of model output (1 Petabyte = 10^{15} bytes) has been distributed to over 4,300 users in several dozen countries. The CMIP-3 multi-model archive has transformed the world of climate science. As of November 2010, over 560 peer-reviewed publications used CMIP-3 data. These publications formed the scientific backbone of the IPCC FAR. The CMIP-3 archive provided the basis for roughly 75% of the figures in Chapters 8-11 of the Fourth Assessment Report, and for 4 of the 7 figures in the IPCC "Summary for Policymakers" (10).

The CMIP-3 database can be used by anyone, free of charge. It is one of the most successful data-sharing models in any scientific community – not just the climate science community.

6. Accommodation of "alternative" views in the IPCC

Some parties critical of the IPCC have claimed that it does not accommodate the full range of scientific views on the subject of the nature and causes of climate change. In my opinion, such claims are specious. I would contend that all four previous IPCC Assessments (3, 4, 9, 10) have dealt with "alternative viewpoints" in a thorough and comprehensive way. The IPCC reports have devoted extraordinary scientific attention to a number of highly-publicized (and incorrect) claims.

Examples include the claim that the tropical lower troposphere cooled over the satellite era; that the water vapor feedback is zero or negative; that variations in the Sun's energy output explain all observed climate change. The climate science community has not dismissed these claims out of hand. Scientists have done the research necessary to determine whether these "alternative viewpoints" are scientifically credible, and have shown that they are not.

7. Concluding Thoughts

My job is to evaluate climate models and improve our scientific understanding of the nature and causes of climate change. I chose this profession because of a deep and abiding curiosity about the world in which we live. The same intellectual curiosity motivates virtually all climate scientists I know.

As my testimony indicates, the scientific evidence is compelling. We know, beyond a shadow of a doubt, that human activities have changed the composition of Earth's atmosphere. And we know that these human-caused changes in the levels of greenhouse gases make it easier for the atmosphere to trap heat. This is simple, basic physics. While there is legitimate debate in the scientific community about the size of the human effect on climate, there is really no serious scientific debate about the scientific finding that our planet warmed over the last century, and that human activities are implicated in this warming.

References and notes

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25 A recent assessment of the U.S. National Academy of Sciences concluded that “It can be said with a high level of confidence that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries” (ref. 26, page 3). The same study also found “it plausible that the Northern Hemisphere was warmer during the last few decades of the 20th century than during any comparable period over the preceding millennium" (ref. 26, pages 3-4).

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28 An example includes testing the null hypothesis that there has been no external forcing of the climate system against the alternative hypothesis that there has been significant external forcing. Currently, all such hypothesis tests rely on model-based estimates of "unforced" climate variability (also known as natural internal variability). This is the variability that arises solely from processes internal to the climate system, such as interactions between the atmosphere and ocean. The El Niño phenomenon is a well-known example of internal climate noise.

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47 Some researchers have argued that most of the observed near-surface warming over the 20th century is attributable to an overall increase in the Sun's energy output. The effect of such an increase would be to warm most of the atmosphere (from the Earth's surface through the stratosphere; see Figure 1, lower left panel). Such behavior is not seen in observations. While temperature measurements from satellites and weather balloons do show warming of the troposphere, they also indicate that the stratosphere has cooled over the past 2-4 decades (ref. 16). Stratospheric cooling is fundamentally inconsistent with a 'solar forcing only' hypothesis of observed climate change, but is consistent with simulations of the response to anthropogenic greenhouse gas increases and ozone decreases (see Figures 1, top left and middle left panels). The possibility of a large solar forcing effect has been further weakened by recent research indicating that changes in solar luminosity on multi-decadal timescales are likely to be significantly smaller than previously thought (refs. 48, 49).

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