Testimony for House Select Committee on Energy Independence and Global Warming

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1. Biographical information

My name is Benjamin Santer. I am a climate scientist. I work at Lawrence Livermore National Laboratory (LLNL) in Livermore, California.

I have been employed since 1992 in LLNL's Program for Climate Model Diagnosis and Intercomparison (PCMDI). 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 of 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 seek to improve 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 by Dr. Stephen Schneider (1).

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"* (2).

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*" (3). 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) had partially masked the warming signal arising from increasing atmospheric concentrations of greenhouse gases (4).

A further major area of progress was the increasing use of "fingerprint" studies (5, 6, 7). 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 (5). They allow researchers to make rigorous tests of competing hypotheses regarding the causes of recent climate change.

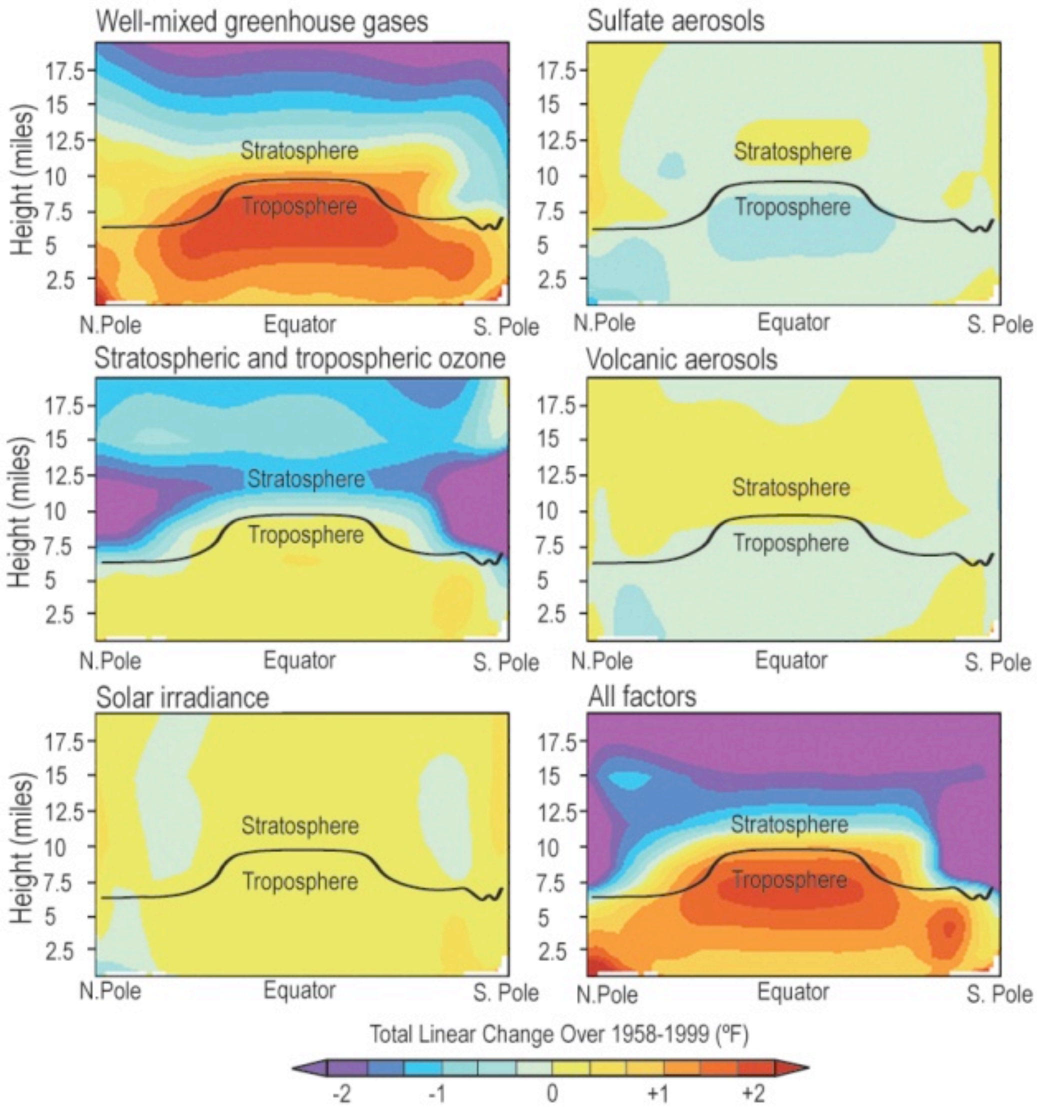

Figure 1: Climate simulations of the vertical profile of temperature change due to five different factors, and the effect due to all factors taken together. The panels above represent a cross-section of the atmosphere from the North Pole to the South Pole, and from the surface up into the stratosphere. The black lines show the approximate location of the tropopause, the boundary between the lower atmosphere (troposphere) and the stratosphere. This Figure is reproduced from Karl *et al.* (8).

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-20^th^ century is <u>very likely</u> 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).

Extraordinary claims require extraordinary proof (12). 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 (13), the Science Academies of eleven nations (14), and the Synthesis and Assessment Products of the U.S. Climate Change Science Plan (15). Many of our professional scientific organizations have also affirmed the reality of a human influence on global climate (16).

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 (17) 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 the detected change to a specific cause or causes (18, 19, 20, 21).

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 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 (22, 23).

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, 24).

4. Evidence from rigorous quantitative fingerprint studies, which compare modeled and observed patterns of climate change.

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 (25) regarding the possible causes of recent climate change (18, 19, 20, 21).

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 ocean heat content (26, 27), Atlantic salinity changes (28), sea-level pressure (29), tropopause height (30), zonal-mean rainfall (31), surface humidity (32), atmospheric moisture (33, 34), and Arctic sea ice extent (35). 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 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 (36) are physically consistent with increases in ocean heat content (37, 38) and near-surface temperature (39, 40).

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 (41). 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 (42, 43, 44).

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 (45). 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 (46, 47, 48, 49).

Because regional-scale climate changes will determine societal impacts, fingerprint studies are increasingly shifting their focus from global to regional scales. 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 (50), so that identifying any human-caused climate signal 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 (51, 52). Examples include human-induced changes in land surface properties (53) or in the concentrations of carbon-containing aerosols (54, 55). Neglect or inaccurate specification of these factors complicates D&A studies.

Despite these problems, numerous studies 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 (56, 57, 58, 59). Related work (60, 61) suggests that an human-caused climate signal has already emerged from the background noise at even smaller spatial scales (at or below 500 km) (62), and may be contributing to regional changes in the distributions of plant and animal species (63).

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 (64, 65, 66, 67, 68).

The Microwave Sounding Unit Debate

For over a decade, scientists critical of “fingerprint” studies have argued that tropospheric temperature measurements from satellites and weather balloons (radiosondes) show little or no warming of the troposphere over the past several decades, while climate models indicate that that the troposphere should have warmed markedly in response to increases in greenhouse gases (see Figure 1, upper left panel). This apparent discrepancy between climate model estimates and observations has been used to cast doubt on the reality of a “discernible human influence” on the climate system (69).

It is unquestionable that satellites have transformed our scientific understanding of the weather and climate of planet Earth. Since 1979, Microwave Sounding Units (MSU) on polar-orbiting satellites have measured the microwave emissions of oxygen molecules in the atmosphere. These emissions are proportional to atmospheric temperatures. By monitoring microwave emissions at different frequencies, scientists can obtain information about the temperatures of broad atmospheric layers. Most attention has focused on the temperatures of the lower stratosphere and mid- to upper troposphere (T_4 and T_2, respectively) as well as on an estimate of lower tropospheric temperatures (T_{2LT}) (70).

The first attempts to obtain climate records from MSU data were made by scientists at the University of Alabama in Huntsville (UAH) (71, 72, 73). Until recently, the UAH group's analysis of the MSU data suggested that the tropical lower troposphere had cooled since 1979. Concerns regarding the reliability of the MSU-based tropospheric temperature trends were countered with the argument that weather balloons also suggested cooling of the tropical troposphere (74), and constitute a completely independent temperature monitoring system (75, 76).

Throughout most of the 1990s, only one group (the UAH group) was actively working on the development of temperature records from MSU data. In 1998, the Remote Sensing Systems (RSS) group in California identified a problem in the UAH data related to the progressive orbital decay and altitude loss over the lifetimes of individual satellites. This introduced a spurious cooling trend in the UAH data (77). The RSS scientists (Wentz and Schabel) found that the lower troposphere had warmed over the satellite era.

The UAH group subsequently identified two new corrections that approximately compensated for the cooling influence of orbital degradation. The first correction was related to the effects of orbital drift on the sampling of Earth's diurnal temperature cycle. The second (the so-called "instrument body effect") was due to variations in measured microwave emissions arising from changes in the temperature of the MSU instrument itself, caused by changes in the instrument's exposure to sunlight (78).

Additional research cast doubt on the UAH results. Three separate groups found that the mid- to upper troposphere had warmed markedly over the satellite era (79, 80, 81, 82, 83, 84, 85), in contrast to the UAH results (74, 78). The UAH group, however, continued to claim close correspondence between their own MSU-based estimates of tropospheric temperature trends and trends derived from weather balloons (“radiosondes”) (74). This raised critical questions regarding the quality of radiosonde temperature measurements. Were these measurements an unambiguous gold standard?

Recent research indicates that the answer to this question is “no”. The temperature sensors carried by weather balloons have changed over time, as has the shielding that protects the sensors from direct solar heating. Solar heating of the sensors can affect the temperature measurements themselves. The introduction of progressively more effective shielding results in less solar heating, and this in turn imparts a non-climatic cooling trend to the daytime measurements.

Sherwood *et al*. (86) discovered this effect by comparing the radiosonde-based temperature trends based on nighttime ascents (with no solar heating effects) and daytime launches. When this solar heating effect was properly accounted for, weather balloons yielded tropospheric temperature trends that were in better agreement with RSS estimates than with UAH results (86, 87).

Two papers shed further light on these issues. The first paper was by the RSS group, and described a new MSU retrieval of lower tropospheric temperatures (88). RSS obtained substantially larger T_{2LT} trends than UAH (89). Mears and Wentz (88) attributed most of these differences to an error in UAH's method of adjusting for drift in the time of day at which satellites sample the Earth's daily temperature cycle. This error was acknowledged by Christy and Spencer (90). When the UAH group remedied this problem, however, their lower tropospheric trends increased by much smaller amounts than expected on the basis of the RSS analysis (91).

The second paper addressed the physics that governs changes in atmospheric temperature profiles. It compared the relationship between surface and tropospheric temperature changes over a wide range of observational and climate model datasets (92). The focus was on the deep tropics (20°N-20°S), where the UAH and RSS tropospheric temperature trends diverged most markedly. The intent was to investigate whether the simple physics that governs the vertical structure of the tropical atmosphere could be used to constrain the uncertainties in satellite-based trends.

This "simple physics" involves the release of latent heat when moist air rises due to convection and condenses to form clouds. Because of this heat release, tropical temperature changes averaged over large areas (and averaged over sufficient time to damp day-to-day "weather noise") are generally larger in the lower and mid-troposphere than at the surface of the tropical ocean. This "amplification" behavior is well-known from basic theory (93), observations (94), and climate model results (95).

The UAH amplification results were puzzling. For month-to-month fluctuations in tropical temperatures, UAH T_{2LT} anomalies were 1.3 to 1.4 times larger than surface temperature anomalies, consistent with models, theory, and other observational datasets. But for decade-to-decade temperature changes, the UAH T_{2LT} trends were smaller than surface trends, implying that the troposphere damped surface warming. In contrast, the computer model amplification results were consistent across all timescales considered, despite large differences in model structure. Like the models, the RSS observational data also showed similar amplification of surface warming on different timescales.

These results have at least two possible explanations (15, 20, 96). The first is that the UAH data are reliable, and different physical mechanisms control the response of the tropical atmosphere to “fast” and “slow” surface temperature fluctuations. Such time-dependent changes in the physics seem unlikely given our present understanding, and mechanisms that might explain such changes have yet to be identified.

A second explanation is that there are still non-climatic artifacts in the UAH tropospheric temperature records, leading to residual cooling biases in the UAH long-term trend estimates. This is both a simpler and more plausible explanation given the consistency of amplification results across models and timescales, our theoretical understanding of how the tropical atmosphere should respond to sustained surface heating (97), and the currently large uncertainties in observed tropospheric temperature trends (15).

The extraordinary claim that the tropical troposphere had cooled since 1979 has not survived rigorous scrutiny. We have learned that uncertainties in satellite estimates of tropospheric temperature change are far larger than originally believed, and now fully encompass computer model results (98). There is no longer a fundamental discrepancy between modeled and observed estimates of tropospheric temperature changes (15).

Assessing Risks of Changes in Extreme Events

Although we cannot confidently attribute any specific extreme event to human-induced climate change (99), we are capable of making informed scientific statements regarding the influence of human activities on the likelihood of extreme events (100, 101). This is an important distinction.

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 (102). Comparison of the frequencies of extremes in the control and perturbed experiments allows one to make probabilistic statements about how human-induced climate change may have altered the likelihood of the extreme event (48, 102, 103). This is sometimes referred to as an assessment of “fractional attributable risk” (102).

Recently, a “fractional attributable risk” study involving the European summer heat wave of 2003 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*” (102).

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. Conclusions

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 (26, 27, 37, 38, 39, 40, 104). Atmospheric moisture has increased (32, 33, 34, 36). Glaciers have retreated over most of the globe (105, 106, 107). Sea level has risen (108). Snow and sea-ice extent have decreased in the Northern Hemisphere (35, 109, 110). The stratosphere has cooled (111), and there are now reliable indications that the troposphere has warmed (15, 112). The height of the tropopause has increased (30). 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. Personal Thoughts on Harassment of Climate Scientists

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. We care about getting the science right – not about getting rich quick, retiring early, or altering global systems of government.

In April 1994, I was asked to act as Convening Lead Author of Chapter 8 of the IPCC's second assessment report. The chapter was entitled "*Detection of Climate Change and Attribution of Causes*". I did not seek this responsibility. It was offered to me after at least two other scientists had refused the Convening Lead Author job.

Chapter 8 reached the historic conclusion that there is "*a discernible human influence on global climate*". This single sentence changed my life. Immediately after publication of the second assessment report in 1996, I became the subject of Congressional inquiry and unwelcome media attention. I was wrongly accused of "political tampering" and "scientific cleansing", of abuses of the peer-review system, and even of irregularities in my own scientific research.

Responses to these unfounded allegations have been given in a variety of different fora – by myself, by the IPCC, and by other scientists. A complete record of these responses was recently posted on RealClimate.org (113). I refer this post to your attention.

I firmly believe that I would now be leading a different life if my research suggested that there was no human effect on climate. I would not be the subject of Congressional inquiries, Freedom of Information Act requests, or email threats. I would not need to be concerned about the safety of my family. I would not need to be concerned about my own physical safety when I give public lectures.

It is because of the research I do – and because of the findings my colleagues and I have obtained – that I have experienced interference with my ability to perform scientific research.

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 not rocket science. It is simple, basic physics.

Some take comfort in clinging to the false belief that humans do not have the capacity to influence global climate; that we do not need to make any changes in how we produce and use energy; that "business as usual" is good enough for today.

Sadly, "business as usual" will not be good enough for tomorrow. The decisions we reach today will impact the climate future that our children and grandchildren inherit. I think most American want those decisions to be based on the best-available scientific information – not on wishful thinking, or on well-funded disinformation campaigns.

This is one of the defining moments in our country's history, and in the history of our civilization. For a little over decade, we have achieved true awareness of our ever-increasing influence on global climate. We can no longer plead that we were ignorant; that we did not know what was happening. Future generations will judge us on how effectively we addressed the problem of human-caused climate change.

I respectfully request that you do everything in your power to permit my colleagues and I to continue studying the nature and causes of climate change. We need to follow the research wherever it leads us, without fear of the consequences of speaking truth to power.

References and notes

1 Santer, B.D., and T.M.L. Wigley, 2010: Detection and attribution. In: Climate Change Science and Policy [Schneider, S.H., A. Rosencranz, M.D. Mastrandrea, and K. Kuntz-Duriseti (eds.)]. Island Press, Washington D.C., pp. 28-43.

2 Houghton, J.T., *et al*., 1990: *Climate Change. The IPCC Scientific Assessment*. Cambridge University Press, Cambridge, U.K., page xxix.

3 Houghton, J.T., *et al*., 1996: *Climate Change 1995: The Science of Climate Change*. Cambridge University Press, Cambridge, U.K., page 4.

4 Wigley, T.M.L., 1989: Possible climatic change due to SO_2-derived cloud condensation nuclei. *Nature*, **339**, 365-367.

5 Hasselmann, K., 1979: On the signal-to-noise problem in atmospheric response studies. In: *Meteorology of Tropical Oceans* (Ed. D.B. Shaw). Royal Meteorological Society of London, London, U.K., pp. 251-259.

6 Hasselmann, K., 1993: Optimal fingerprints for the detection of time dependent climate change. *Journal of Climate*, **6**, 1957-1971.

7 North, G.R., K.Y. Kim, S.S.P Shen, and J.W. Hardin, 1995: Detection of forced climate signals. Part I: Filter theory. *Journal of Climate*, **8**, 401-408.

8 Karl, T.R., J.M. Melillo, and T.C. Peterson, 2009: Global Climate Change Impacts in the United States. Cambridge University Press, 189 pages.

9 Houghton, J.T., et al., 2001: *Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge, U.K., page 4.

10 IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

11 IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Parry, M. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

12 This phrase is often attributed to the late sociologist Marcello Truzzi http://en.wikipedia.org/wiki/Marcello_Truzzi

13 NRC (National Research Council), 2001: *Climate Change Science. An Analysis of Some Key Questions*. Board on Atmospheric Sciences and Climate, National Academy Press, Washington D.C., 29 pp.

14 Prior to the Gleneagles G8 summit in July 2005, the Science Academies of 11 nations issued a joint statement on climate change (http://www.nasonline.org/site). The statement affirmed the IPCC finding that "most of the warming observed over the last 50 years is attributable to human activities" (ref. 9). The signatories were from the Academia Brasiliera de Ciências, the Royal Society of Canada, the Chinese Academy of Sciences, the Academié des Sciences, France, the Deutsche Akademie der Naturforscher, the Indian National Science Academy, the Accademia dei Lincei, Italy, the Science Council of Japan, the Russian Academy of Sciences, the United Kingdom Royal Society, and the U.S. National Academy of Sciences.

15 Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray (eds.), 2006: *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, 164 pp.

16 See, for example, the position statements on climate change issued by the American Geophysical Union (AGU), the American Meteorological Society (AGU), and the American Statistical Association (ASA). These can be found at: http://www.agu.org/sci_pol/positions/climate_change2008.shtml (AGU); http://www.ametsoc.org/amsnews/2007climatechangerelease.pdf (AMS); and http://www.amstat.org/news/climatechange.cfm (ASA).

17 Mann, M.E., and P.D. Jones, 2003: Global surface temperatures over the past two millenia. *Geophysical Research Letters*, **30**, 1820, doi:10.1029/2003GL017814.

18 Mitchell, J.F.B. *et al*., 2001: Detection of climate change and attribution of causes. In: *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T. *et al*., (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 695-738.

19 IDAG (International Detection and Attribution Group), 2005: Detecting and attributing external influences on the climate system: A review of recent advances. *Journal of Climate*, **18**, 1291-1314.

20 Santer, B.D., J.E. Penner, and P.W. Thorne, 2006: How well can the observed vertical temperature changes be reconciled with our understanding of the causes of these changes? In: *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, pp. 89-108.

21 Hegerl, G.C., F.W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A. Marengo Orsini, J.E. Penner and P.A. Stott, 2007: Understanding and Attributing Climate Change. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 663-745.

22 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. 23, 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. 23, pages 3-4).

23 National Research Council, 2006: *Surface Temperature Reconstructions for the Last 2,000 Years*. National Academies Press, Washington D.C., 196 pp.

24 Examples include increases in surface and tropospheric temperature, increases in atmospheric water vapor and ocean heat content, sea-level rise, widespread retreat of glaciers, *etc*.

25 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.

26 Barnett, T.P. *et al*., 2005: Penetration of human-induced warming into the world's oceans. *Science*, **309**, 284-287.

27 Pierce, D.W. *et al*., 2006: Anthropogenic warming of the oceans: Observations and model results. *Journal of Climate*, **19**, 1873-1900.

28 Stott, P.A., R.T. Sutton, and D.M. Smith, 2008: Detection and attribution of Atlantic salinity changes. *Geophysical Research Letters*, **35**, L21702, doi:10.1029/2008GL035874.

29 Gillett, N.P., F.W. Zwiers, A.J. Weaver, and P.A. Stott, 2003: Detection of human influence on sea level pressure. *Nature*, **422**, 292-294.

30 Santer, B.D. *et al*., 2003: Contributions of anthropogenic and natural forcing to recent tropopause height changes. *Science*, **301**, 479-483.

31 Zhang, X. *et al*., 2007: Detection of human influence on 20th century precipitation trends. *Nature*, **448**, 461-465.

32 Willett, K.M., N.P. Gillett, P.D. Jones, and P.W. Thorne, 2007: Attribution of observed surface humidity changes to human influence. *Nature*, **449**, doi:10.1038/nature06207.

33 Santer, B.D., *et al*., 2007: Identification of human-induced changes in atmospheric moisture content. *Proceedings of the National Academy of Sciences*, **104**, 15248-15253.

34 Santer, B.D., *et al*., 2009: Incorporating model quality information in climate change detection and attribution studies. *Proceedings of the National Academy of Sciences*, **106**, 14778-14783.

35 Min, S.-K., X. Zhang, F.W. Zwiers, and T. Agnew, 2008: Human influence on Arctic sea ice detectable from early 1990s onwards. *Geophysical Research Letters*, **35**, L21701, doi:10.1029/2008GL035725.

36 Trenberth, K.E., J. Fasullo, and L. Smith, 2005: Trends and variability in column-integrated atmospheric water vapor. *Climate Dynamics*, **24**, doi:10.1007/s00382-005-0017-4.

37 Levitus, S., J.I. Antonov, and T.P. Boyer, 2005: Warming of the world ocean, 1955-2003. *Geophysical Research Letters*, **32**, L02604, doi:10.1029/2004GL021592.

38 Domingues, C.M., *et al*., 2008: Rapid upper-ocean warming helps explain multi-decadal sea-level rise, *Nature*, **453**, 1090-1093.

39 Jones, P.D., M. New, D.E. Parker, S. Martin, and I.G. Rigor, 1999: Surface air temperature and its changes over the past 150 years. *Reviews of Geophysics*, **37**, 173-199.

40 Brohan, P., J.J. Kennedy, I. Harris, S.F.B. Tett, and P.D. Jones, 2006: Uncertainty estimates in regional and global observed temperature changes: A new dataset from 1850. *Journal of Geophysical Research*, **111**, D12106, doi:10.1029/2005JD006548.

41 The argument here is that some anthropogenic "forcings" of climate (particularly the so-called indirect forcing caused by the effects of anthropogenic aerosols on cloud properties) are highly uncertain, so that many different combinations of these factors could yield the same global-mean changes. While this is a valid concern for global-mean temperature changes, it is highly unlikely that different combinations of forcing factors could produce the same complex space-time patterns of climate change (see Figure 1).

42 Some researchers have argued that most of the observed near-surface warming over the 20th century is attributable to an overall increase in solar irradiance. 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 radiosondes do show warming of the troposphere, they also indicate that the stratosphere has cooled over the past 2-4 decades (ref. 15). 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 GHG 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. 43, 44).

43 Foukal, P., G. North, and T.M.L. Wigley, 2004: A stellar view on solar variations and climate. *Science*, **306**, 68-69.

44 Foukal, P., C. Fröhlich, H. Spruit, and T.M.L. Wigley, 2006: Physical mechanisms of solar luminosity variation, and its effect on climate. *Nature*, **443**, 161-166.

45 In order to assess whether observed climate changes over the past century are truly unusual, we require information on the amplitude and structure of climate noise on timescales of a century or longer. Unfortunately, direct instrumental measurements are of insufficient length to provide such information. This means that D&A studies must rely on decadal- to century-timescale noise estimates from computer model control runs.

46 Allen, M.R., and S.F.B. Tett, 1999: Checking for model consistency in optimal fingerprinting. *Climate Dynamics*, **15**, 419-434.

47 Thorne, P.W. *et al*., 2003: Probable causes of late twentieth century tropospheric temperature trends. *Climate Dynamics*, **21**, 573-591.

48 Santer, B.D. *et al*., 2006: Causes of ocean surface temperature changes in Atlantic and Pacific tropical cyclogenesis regions. *Proceedings of the National Academy of Sciences*, **103**, 13905-13910.

49 AchutaRao, K.M., M. Ishii, B.D. Santer, P.J. Gleckler, K.E. Taylor, T.P. Barnett, D.W. Pierce, R.J. Stouffer, and T.M.L. Wigley, 2007: Simulated and observed variability in ocean temperature and heat content. *Proceedings of the National Academy of Sciences*, **104**, 10768-10773.

50 Wigley, T.M.L., and P.D. Jones, 1981: Detecting CO_2-induced climatic change. *Nature*, **292**, 205-208.

51 Ramaswamy, V., *et al*., 2001: Radiative forcing of climate change. In: *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T. *et al*., (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 349-416.

52 NRC (National Research Council), 2005: *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*. Board on Atmospheric Sciences and Climate, National Academy Press, Washington D.C., 168 pp.

53 Feddema, J. *et al*., 2005: A comparison of a GCM response to historical anthropogenic land cover change and model sensitivity to uncertainty in present-day land cover representations. *Climate Dynamics*, **25**, 581-609.

54 Penner, J.E. *et al*., 2001: Aerosols, their direct and indirect effects. In: *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T. *et al*. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 289-348.

55 Menon, S., J. Hansen, L. Nazarenko, and Y.F. Luo, 2002: Climate effects of black carbon aerosols in China and India. *Science*, **297**, 2250-2253.

56 Stott, P.A., 2003: Attribution of regional-scale temperature changes to anthropogenic and natural causes. *Geophysical Research Letters*, **30**, doi: 10.1029/2003GL017324.

57 Zwiers, F.W., and X. Zhang, 2003: Towards regional-scale climate change detection. *Journal of Climate*, **16**, 793-797.

58 Karoly, D.J. *et al*., 2003: Detection of a human influence on North American climate. *Science*, **302**, 1200-1203.

59 Min, S.-K., A. Hense, and W.-T. Kwon, 2005: Regional-scale climate change detection using a Bayesian detection method. *Geophysical Research Letters*, **32**, L03706, doi:10.1029/2004GL021028.

60 Karoly, D.J., and Q. Wu, 2005: Detection of regional surface temperature trends. *Journal of Climate*, **18**, 4337-4343.

61 Knutson, T.R. *et al*., 2006: Assessment of twentieth-century regional surface temperature trends using the GFDL CM2 coupled models. *Journal of Climate*, **19**, 1624-1651.

62 Knutson *et al*. (ref. 61) state that their "*regional results provide evidence for an emergent anthropogenic warming signal over many, if not most, regions of the globe*".

63 Root, T.L., D.P. MacMynowski, M.D. Mastrandrea, and S.H. Schneider, 2005: Human-modified temperatures induce species changes: Joint attribution. *Proceedings of the National Academy of Sciences*, **102**, 7465-7469.

64 Examples include snowpack depth (refs. 65, 66), maximum and minimum temperatures in mountainous regions of the western U.S. (refs. 65, 67), and the timing of streamflow in major river basins (refs. 65, 68).

65 Barnett, T.P., *et al*., 2008: Human-induced changes in the hydrology of the western United States. *Science*, **319**, 1080-1083.

66 Pierce, D.W., *et al*., 2008: Attribution of declining western U.S. snowpack to human effects. *Journal of Climate*, **21**, 6425-6444.

67 Bonfils, C., *et al*., 2008: Detection and attribution of temperature changes in the mountainous Western United States. *Journal of Climate*, **21**, 6404-6424.

68 Hidalgo, H., *et al*., 2009: Detection and attribution of streamflow timing changes to climate change in the western United States. *Journal of Climate*, **22**, 3838-3855.

69 See, for example, an op-ed by James Schlesinger (former Secretary of Energy, Secretary of Defense, and Director of the CIA) in the January 22, 2004 edition of the *Los Angeles Times*. Mr. Schlesinger noted that "...*the theory that increasing concentrations of greenhouse gases like carbon dioxide will lead to further warming is at least an oversimplification. It is inconsistent with the fact that satellite measurements over 35 years (sic) show no significant warming in the lower atmosphere, which is an essential part of the global-warming theory*".

70 The designations T_4 and T_2 reflect the fact that the original MSU measurements employed MSU channels 4 and 2 (subsequently replaced by equivalent data from other channels in the latest Advanced Microwave Sounding Units). The bulk of the microwave emissions monitored by channel 4 is from roughly 14 to 29 km above Earth's surface (150 to 15 hPa). Channel 2 primarily samples emissions from the surface to 18 km (75 hPa). The T_{2LT} retrieval is constructed using the outer and inner "scan angles" of channel 2, and is a measure of temperatures from the surface to 8 km (350 hPa). For further details of the atmospheric layers sampled by MSU, see ref. 15.

71 Spencer, R.W., and J.R. Christy, 1990: Precise monitoring of global temperature trends from satellites. *Science*, **247**, 1558-1562.

72 Spencer, R.W., and J.R. Christy, 1992: Precision and radiosonde validation of satellite grid-point temperature anomalies, Part I, MSU channel 2. *Journal of Climate*, **5**, 847-857.

73 Spencer, R.W., and J.R. Christy, 1992: Precision and radiosonde validation of satellite grid-point temperature anomalies, Part II, A tropospheric retrieval and trends during 1979-90. *Journal of Climate*, **5**, 858-866.

74 Christy, J.R., R.W. Spencer, W.B. Norris, W.D. Braswell, and D.E. Parker, 2003: Error estimates of version 5.0 of MSU-AMSU bulk atmospheric temperatures. *Journal of Atmospheric and Oceanic Technology*, **20**, 613-629.

75 The true degree of independence is uncertain. In their early work, the UAH group apparently relied on radiosonde-derived temperatures to choose between different possible "adjustment pathways" in the complex process of correcting MSU data for known inhomogeneities (see ref. 76).

76 Christy, J.R., R.W. Spencer, and E.S. Lobl, 1998: Analysis of the merging procedure for the MSU daily temperature time series. *Journal of Climate*, **11**, 2016-2041.

77 Wentz, F.J., and M. Schabel, 1998: Effects of orbital decay on satellite-derived lower-tropospheric temperature trends. *Nature*, **394**, 661-664.

78 Christy, J.R., R.W. Spencer, and W.D. Braswell, 2000: MSU Tropospheric temperatures: Data set construction and radiosonde comparisons. *Journal of Atmospheric and Oceanic Technology*, **17**, 1153-1170.

79 The three groups involved were at RSS (ref. 80), the University of Maryland (UMD) (refs. 81, 82), and the University of Washington/NOAA (UW) (refs. 83, 84). The RSS, UMD, and STAR groups independently reprocessed the raw T_2 data used by UAH, using different adjustment procedures to account for orbital drift and instrument body effects. In the RSS and UMD analyses, the mid- to upper troposphere warmed by 0.1 to 0.2°C/decade over the satellite era. These values were substantially larger than the satellite era T_2 trends estimated by UAH, which ranged from 0.02 to 0.04°C/decade. The UW group applied a statistical approach to quantify and remove the influence of stratospheric cooling on MSU T_2 data (refs. 83, 84). This enhanced the estimated warming of the mid- to upper troposphere in both the UAH and RSS datasets. The approach also highlighted the physically-implausible behavior of the UAH group's tropical T_2 and T_{2LT} trends, which showed sustained warming and cooling (respectively) of adjacent layers of the troposphere (ref. 84). More recently, a fourth research group at the NOAA/NESDIS Center for Satellite Applications and Research (STAR) (ref. 85) has also developed an MSU T_2 temperature record. The STAR group has employed a novel method to intercalibrate the MSU instruments flown on different satellites. The STAR tropospheric temperature change estimates (like those of the RSS, UMD, and UW groups) show substantial warming of the mid- to upper troposphere, but are only available from 1987 onwards.

80 Mears, C.A., M.C. Schabel, and F.W. Wentz, 2003: A reanalysis of the MSU channel 2 tropospheric temperature record. *Journal of Climate*, **16**, 3650-3664.

81 Vinnikov, K.Y., and N.C. Grody, 2003: Global warming trend of mean tropospheric temperature observed by satellites. *Science*, **302**, 269-272.

82 Vinnikov, K.Y. *et al*., 2006: Temperature trends at the surface and the troposphere. *Journal of Geophysical Research*, doi:10.1029/2005jd006392.

83 Fu, Q., C.M. Johanson, S.G. Warren, and D.J. Seidel, 2004: Contribution of stratospheric cooling to satellite-inferred tropospheric temperature trends. *Nature*, **429**, 55-58.

84 Fu, Q., and C.M. Johanson, 2005: Satellite-derived vertical dependence of tropical tropospheric temperature trends. *Geophysical Research Letters*, **32**, L10703, doi:10.1029/2004GL022266.

85 Zou, C.-Z., M. Gao, and M.D. Goldberg, 2009: Error structure and atmospheric temperature trends in observations from the Microwave Sounding Unit. *Journal of Climate*, **22**, 1661-1681.

86 Sherwood, S.C., J. Lanzante, and C. Meyer, 2005: Radiosonde daytime biases and late 20th century warming. *Science*, **309**, 1556-1559.

87 Randel, W.J., and F. Wu, 2006: Biases in stratospheric temperature trends derived from historical radiosonde data. *Journal of Climate*, **19**, 2094-2104.

88 Mears, C.A., and F.W. Wentz, 2005: The effect of diurnal correction on satellite-derived lower tropospheric temperature. *Science*, **309**, 1548-1551.

89 The RSS estimate of the global-mean T_{2LT} trend over 1979 to 2003 was 0.1°C/decade warmer than the UAH estimate (0.193 versus 0.087°C/decade, respectively). Differences were even larger in the tropics, where the lower troposphere cooled in the UAH data (by 0.015°C/decade), but warmed markedly in the RSS analysis (by 0.189°C/decade) (see ref. 88).

90 Christy, J.R., and R.W. Spencer, 2005: Correcting temperature data sets. *Science*, **310**, 972.

91 The UAH global-mean T_{2LT} trend over December 1978 to July 2005 increased by only 0.035°C/decade (to 0.123°C/decade). This change was stated to be "within our previously published error margin of ±0.05K/decade" (ref. 90).

92 Santer, B.D. *et al*., 2005: Amplification of surface temperature trends and variability in the tropical atmosphere. *Science*, **309**, 1551-1556.

93 Hess, S.L., 1959. *Introduction to Theoretical Meteorology*. Holt, Rinehart and Winston, New York, 362 pp.

94 Wentz, F.J., and M. Schabel, 2000: Precise climate monitoring using complementary satellite data sets. *Nature*, **403**, 414-416.

95 Manabe, S., and R.J. Stouffer, 1980: Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere. *Journal of Geophysical Research*, **85**, 5529-5554.

96 Wigley, T.M.L. *et al*., 2006: Executive Summary. In: *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, pp. 1-14.

97 Prolonged surface warming should destabilize tropical temperature profiles, thus producing the conditions necessary for moist convection and readjustment of atmospheric temperatures to a moist adiabatic lapse rate (66).

98 Santer, B.D., *et al*., 2008 :Consistency of modeled and observed temperature trends in the tropical troposphere. *International Journal of Climatology*, **28**, 1703-1722.

99 Allen, M.R., 2003: Liability for climate change. *Nature*, **421**, 891-892.

100 Wigley, T.M.L., 1988: The effect of changing climate on the frequency of absolute extreme events. *Climate Monitor*, **17**, 44-55.

101 Meehl, G.A., and C. Tebaldi, 2004: More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, **305**, 994-997.

102 Stott, P.A., D.A. Stone, and M.R. Allen, 2004: Human contribution to the European heatwave of 2003. *Nature*, **423**, 61-614.

103 Tebaldi, C., K. Hayhoe, J.M. Arblaster, and G.A. Meehl, 2006: Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Climatic Change*, **79**, 185-211.

104 Jones, P.D, and A. Moberg, 2003: Hemispheric and large scale surface air temperature variations: an extensive revision and an update to 2001. *Journal of Climate*, **16**, 206-223.

105 Arendt, A.A. *et al*., 2002: Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science*, **297**, 382-386.

106 Paul, F., A. Kaab, M. Maisch, T. Kellenberger, and W. Haeberli, 2004: Rapid disintegration of Alpine glaciers observed with satellite data. *Geophysical Research Letters*, **31**, L21402,doi:10.1029/2004GL020816.

107 Meier, M.F., et al., 2007: Glaciers dominate eustatic sea-level rise in the 21st century. *Science*, **317**, 1064-1067.

108 Cazenave, A., and R.S. Nerem, 2004: Present-day sea level change: Observations and causes. *Reviews of Geophysics*, **42**, RG3001, doi:10.1029/2003RG000139.

109 Vinnikov, K.Y. *et al*., 1999: Global warming and Northern Hemisphere sea ice extent. *Science*, **286**, 1934-1937.

110 Stroeve, J., *et al*., 2008: Arctic sea ice plummets in 2007. *EOS*, **89**, 2, 13-14.

111 Ramaswamy, V. *et al*., 2006: Anthropogenic and natural influences in the evolution of lower stratospheric cooling. *Science*, **311**, 1138-1141.

112 Trenberth K.E., *et al*., 2007: Observations: Surface and atmospheric climate change. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. [Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 235-336

113 Santer, B.D., 2010: Close encounters of the absurd kind. See http://www.realclimate.org/index.php/archives/2010/02/close-encounters-of-the-absurd-kind/