

# How Much Will the World Warm?

By Kevin Hamilton

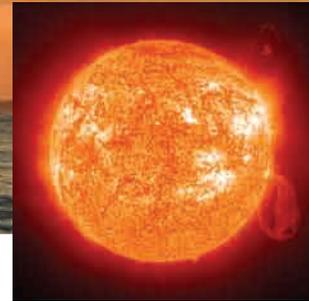
A key challenge for climate science is predicting how the global-mean temperature will respond to anticipated changes in radiative forcing produced by human activities, such as emissions of long-lived greenhouse gases and other pollutants. While the practical effects of climate change will be felt locally and involve other variables besides surface temperature, the overall strength and significance of climate change will be determined by the magnitude of the global-mean warming. Estimating this surface warming in response to projected changes in atmospheric CO<sub>2</sub> concentration was the goal of the early classic studies of climate change – notably the first radiative-convective-equilibrium model studies in the mid-1960s by **Suki Manabe**, **Fritz Möller** and **Richard Wetherald**, and the first climate change studies with comprehensive general circulation models in the mid-1970s by Manabe and Wetherald. One of the first formal assessments of the problem was by the 1979 US

National Academy of Sciences (NAS) panel chaired by **Julie Charney**. The panel concluded that a doubling of atmospheric CO<sub>2</sub> concentration would lead to a global warming of the surface of between 1.5°C and 4.5°C.

The assessments by the Intergovernmental Panel on Climate Change (IPCC) published in 1990, 1995, 2001 and 2007 have all included a review of predictions of the equilibrium warming to a doubling of atmospheric CO<sub>2</sub>. The 1990 assessment included results from 22 atmospheric general circulation models (GCMs) that were mainly coupled with simplified representations of the ocean heat storage and transport. These various models predicted a warming of between 1.9°C and 4.8°C. By the Fourth IPCC report in 2007 (AR4) results from 19 fully coupled comprehensive ocean-atmosphere GCMs were available, and they predict equilibrium warming for double CO<sub>2</sub> conditions between 2.1°C and 4.4°C, a range not much narrower than that determined in the NAS study almost 3 decades earlier!

*Climate sensitivity* is a measure of the strength of the connection between a perturbation to Earth's radiation balance due to greenhouse gases, aerosols, or other natural or anthropogenic forcings, and the resulting change in global-mean surface temperature. High climate sensitivity means the climate system responds strongly to a radiative perturbation and produces a comparatively large temperature change (and correspondingly large changes in other climate variables). As noted above, the present array of state-of-the-art GCMs displays a disconcertingly wide range of sensitivity to the same radiative perturbation. Here I will discuss only what is sometimes called the “Charney sensitivity,” which considers just rapid feedbacks such as those from water vapor, clouds, snow or ice cover, etc., but not possible feedbacks that might arise from slower processes in the cryosphere, biosphere, or deep ocean.

It is natural to ask if the real climate sensitivity can be constrained empirically using evidence of past

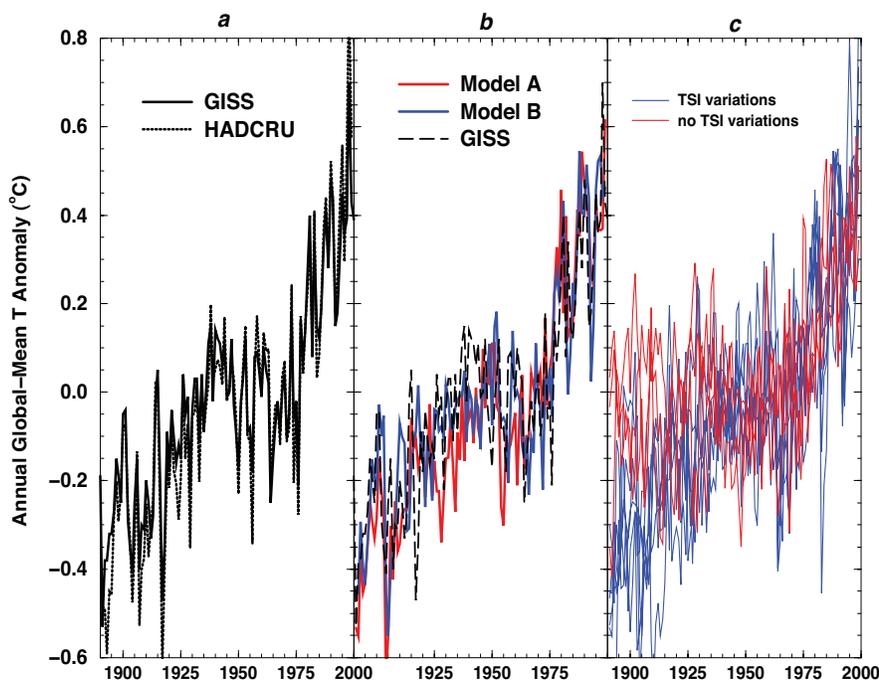


climate behavior. One possibility is to look into the distant past and try to validate comprehensive models by seeing if they can consistently account for proxy reconstructions of such variables as ice cover and temperature during a particular climate period (e.g., Last Glacial Maximum). For the last 150 years, we can use the instrumental record of global-mean temperatures. Two principal approaches have been developed in this latter regard: examining the response of the climate system to transient radiative perturbations caused by volcanic eruptions, and analyzing the overall global warming record of the late-19<sup>th</sup> through 20<sup>th</sup> century.

## Radiative Perturbations by Volcanic Eruptions

Research on volcanic effects has focused mostly on the aftermath of the 1991 eruption of Mt. Pinatubo in the Philippines, the largest and best observed major eruption of the 20<sup>th</sup> century. The results claimed in the published literature on this subject are broadly consistent with the wide range of equilibrium sensitivities seen in the IPCC models. Here at the IPRC we examined the issue of how well observations of the climate effects of a Pinatubo-like eruption constrain climate sensitivity. Our conclusions (Boer et al., 2007) suggest that with present-day observational capabilities it may be dif-

ficult to use volcanic effects to tightly constrain climate sensitivity. Part of the difficulty is that the climate forcing from a volcano is fairly short-lived and climate feedbacks do not have a chance to be strongly activated. Another problem is the difficulty of accounting for unforced natural variability in the relatively short periods of interest. The situation could be improved if the full global-mean energy budget, including the rate of energy storage in the ocean and cryosphere, could be accurately observed. Despite recent advances in observational capabilities, the required accuracy to close the global-energy budget has still not been achieved (Trenberth and Fasullo, 2010).



**Figure 1.** The annual global-mean surface air temperature expressed as a deviation from the 1951-1980 mean. (a) for two observational data sets produced by the Goddard Institute for Space Studies (GISS) and the University of East Anglia Climate Research Unit (HADCRU) (b) results from forced 20<sup>th</sup> century climate simulations from two different coupled GCMs (“A” and “B”) compared with the GISS observations, (c) results from 8 different coupled GCMs. Results from models with no total solar irradiance variation imposed are shown in red.

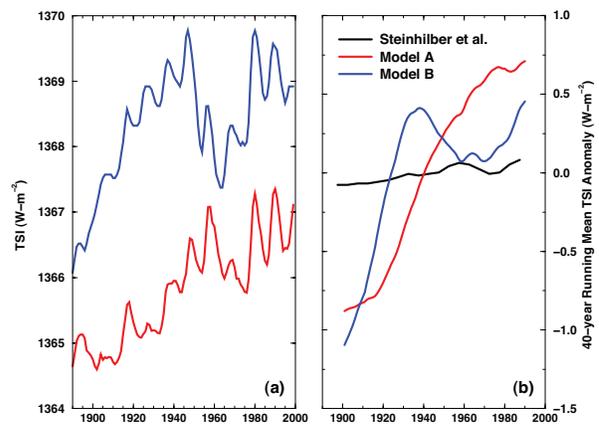
## The 20th Century Global Warming

In order to assess the climate sensitivity to future changes in long-lived greenhouse gas (LLGHG) concentrations, it seems obvious to look at the observed warming of the last 100–150 years, a period that should have been strongly affected by anthropogenic increases in LLGHG. Figure 1a shows the time series of annual-mean surface temperatures from two observational data sets from 1890 to 2000 expressed as deviations from the 1951 – 1980 mean. Taking the difference between the first and last decades of the 20<sup>th</sup> century in Figure 1 yields a warming of about 0.6°C, sometimes loosely quoted as the observed anthropogenic effect on 20<sup>th</sup> century global warming.

The figure, however, shows that the observations have a rather complicated structure. The warming appears to have occurred mostly in two spurts: during 1900–1940 and 1970–2000. This complicates the attribution of the warming because both fossil fuel CO<sub>2</sub> emissions and the increase in radiative forcing from LLGHG accelerated sharply in the second half of the century. From the IPCC AR4 (Figure 2.23), it appears the global-mean radiative forcing due to LLGHG increased by about 0.35 W/m<sup>2</sup> between 1900 and 1940, which is much less than the roughly 1.2 W/m<sup>2</sup> increase that occurred between 1960 and 2000. Considering the temperature changes across the entire 20<sup>th</sup> century, therefore, has the danger of “attributing the warming before 1940 to the CO<sub>2</sub> emitted after 1950”! (I have paraphrased a remark by Massachusetts Institute of Technology professor and prominent critic of the mainstream climate change consensus, **Richard Lindzen**). Our understanding of the multi-decadal details in Figure 1 is hampered by considerable uncertainty about non-LLGHG forcings (e.g., effects of aerosols on clouds, solar irradiance variations, and others) as well as lack of knowledge of the natural unforced variability of the global climate at multi-decadal scales.

The AR4 GCM intercomparison included “climate of the 20<sup>th</sup> century” (20C3M) runs in which the models had a representation of the changing climate forcings due to LLGHGs, other anthropogenic pollution, solar variations, and volcanic eruptions. As a project in my graduate climate course at the University of Hawai‘i last year, the students (**Bob Ballard, Ying Chen, Hiroyuki Ito, Julie Kelly, Thien Van Le, Chase Norton, Kat Scanlon, Chuan-Chi Tu, Baoqiang Xiang**) and I tried to assess how well individual models reproduced the observed temperature time series and whether the results had implications for global-climate sensitivity.

If we define the total 20<sup>th</sup> century warming as the mean of the 1980–1999 period minus the mean of the 1891–1910 period, the two observational data sets in Figure 1a indicate warmings of 0.6° C (GISS) and 0.7°C (HADCRU). We examined the results for single realizations from 14 of the AR4 GCMs and found this warming ranged from 0.23°C to 0.97°C. Some models do a rather poor job in reproducing the details of the observed warming evolution; others, however, do quite well in reproducing the observed early 20<sup>th</sup> century as well as the late 20<sup>th</sup> century warming. Results for two of the GCMs that display particularly realistic-looking simulations are shown in Figure 1b.



**Figure 2. (a) Annual-mean total solar irradiance imposed in the forced 20<sup>th</sup> century runs for model “A” (red) and model “B” (blue). (b) 40-year running means of the total solar irradiance in models “A” and “B” compared with the recent observational inference from Steinhilber et al.**

Figure 1c shows the results for a randomly chosen subset of 8 of the models. The difference between the models that simulate a realistic early 20<sup>th</sup> century warming (blue curves) versus those that do not (red curves) is quite apparent. The blue curves are for models that included a significant variation in total solar irradiance (TSI) while the red curves are for models with constant TSI throughout the run. This pattern seems to be rather consistent among the models analyzed. Characterizing the early 20<sup>th</sup> century warming as the 1941–1950 mean minus 1901–1910 mean, the average for the 6 models with TSI variations is 0.26°C, while it is just 0.05°C for the 8 models without significant TSI variations. The observed values for this warming are 0.27°C (GISS) and 0.31°C (HADCRU).

So it is apparent that typical GCMs reproduce the observed early 20<sup>th</sup> century warming only if a significantly rising solar forcing during that period is included. However, we have accurate direct observations of TSI only after 1978. These have shown a peak-to-peak TSI variation of roughly 1 W/m<sup>2</sup> over the 11-year solar activity cycle, and fairly consistent values from cycle-to-cycle over the last three decades. Figure 2a shows the annual-mean TSI used in the two models whose temperatures are plotted in Figure 1b. Their post-1978 TSI values are similar (except for about a 2.5 W/m<sup>2</sup> mean offset, which is not important for present purposes). The evolution of the pre-1978 TSI values used in these models is based on published studies by solar physicists in the 1990s who had inferred TSI from indirect reconstructions. The recent advances in the field now point to much less

multidecadal variability in TSI. The black curve in Figure 2b shows 40-year mean values of TSI from the recent study of Steinhilber et al. (2009), who based their analysis on ice-core observations of the concentration of  $^{10}\text{Be}$ , an isotope whose production in the atmosphere by cosmic rays is modulated by the solar magnetic field (which in turn is related to solar luminosity). These inferred results show much less increase in the early 20<sup>th</sup> century than the TSI values used in the two GCMs.

The role of solar variability in affecting global mean temperatures on decadal-century scales has been investigated in many earlier studies, of course. Also there have been sophisticated studies of the variability of the 20<sup>th</sup> century temperature record as simulated in different GCMs and the connection of the results with the imposed climate forcings (such studies often focused on identifying an anthropogenic temperature signal). However, as far as I can tell, no earlier reference has highlighted the very elementary point that the biggest differences among 20<sup>th</sup> century simulations among the AR4 GCMs are due the very different TSI variations imposed, and that perhaps unrealistically large variations in TSI are needed for typical state-of-the-art GCMs to reproduce the basic features of the observed 20<sup>th</sup> century temperature record.



Mt. St. Helens erupting on May 18, 1980. Photo courtesy USGS

This analysis shows the difficulty in using the 20<sup>th</sup> century warming as a guide to validating model climate sensitivity. The uncertainties in forcing are large, and it is unclear whether current models can actually account for the observed early 20<sup>th</sup> century warming if they are forced with realistic solar forcing.

There are perhaps ways to resolve this problem, for example, if the multidecadal fluctuations in the global-mean temperature record are largely driven by internal variations rather than responding to global-climate forcing. However, one hypothesis that cannot be ruled out is that the real climate is actually more sensitive than any of the current GCMs predicts, and that the early 20<sup>th</sup> century warming was a response to the relatively modest LLGHG forcing increase during that period. Under this hypothesis, the absence of accelerated warming after 1940 could be attributed to the growth of negative forcings (notably from tropospheric aerosol pollution but also from a modest contribution of the stratospheric effects of large volcanic eruptions, which were more prevalent in the last 4 decades of the 20<sup>th</sup> century than in the first half).

## First-Principles Modeling of Climate Feedbacks?

It seems we are some distance from comprehensive climate models that are realistic enough to believe their simulations of the global-mean temperature. Large uncertainties remain in the treatment of the effects of processes with scales that are too small to explicitly resolve in the finite numerical representation of present-day global models. Intercomparisons of state-of-the-art GCMs suggest that some key processes determine climate sensitivity, such as water vapor feedback and ice and snow albedo feedback are quite similar among the models. The simulations of how clouds respond in climate change, however, differ greatly and these differences in the cloud feedbacks account for almost all the intermodel spread in simulated global-climate sensitivity. It is this representation of cloud processes that is notoriously challenging for climate modeling and much remains to be done before GCM cloud simulations can be considered successful.

Our work at the IPRC on validating GCM simulations of large-scale cloud fields against satellite observations has demonstrated significant problems. As an example, Figure 3 shows how greatly the annual-mean cloud liquid water

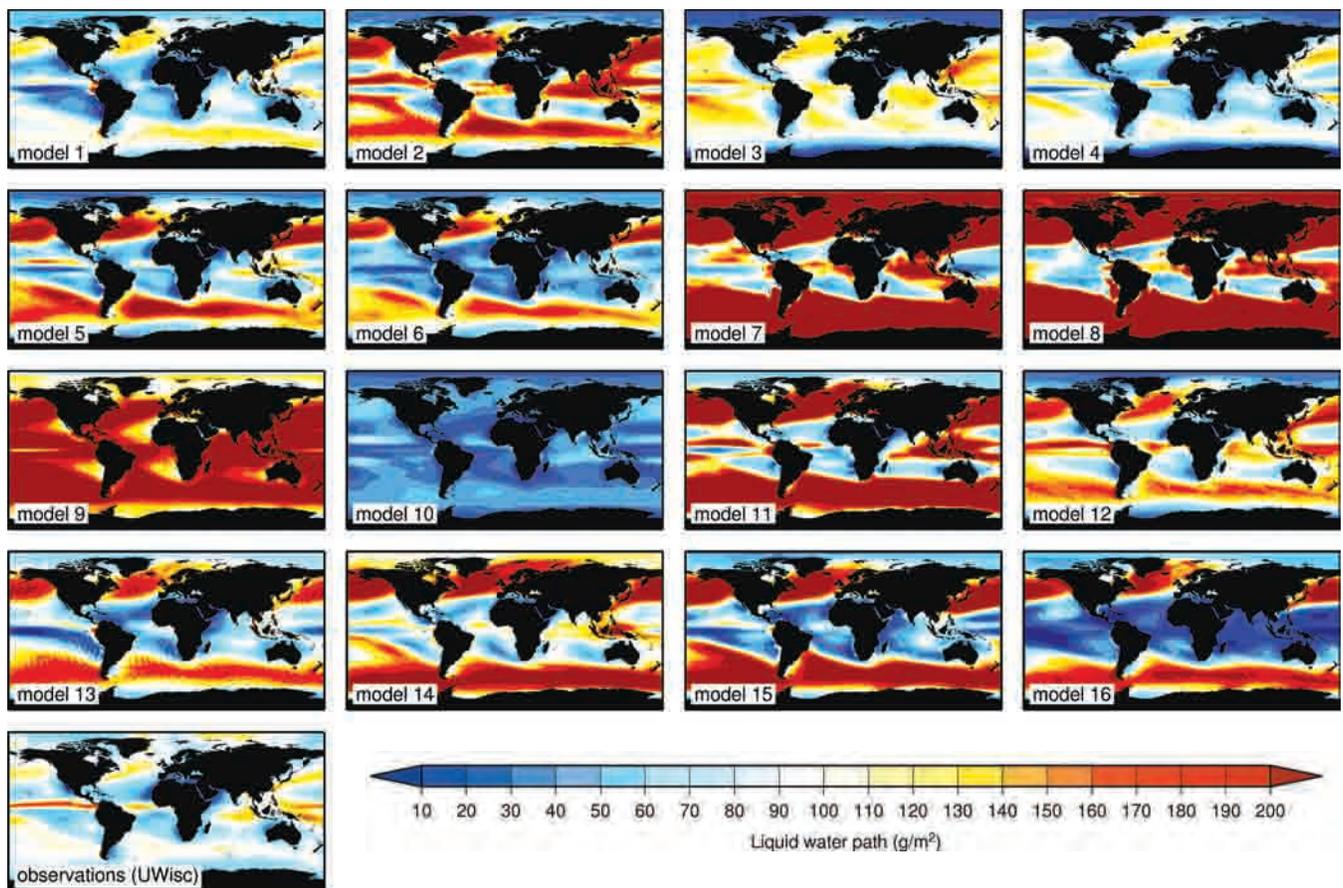


Figure 3. The annual-mean liquid water path simulated in present-day runs by 16 different coupled GCMs compared with observations (bottom left).

content in 16 present-day GCM simulations differ from microwave satellite observations. Problems are also seen in the GCM simulations of fractional cloud cover and the cloud-climate forcing. Studies here at the IPRC (Stowasser and Hamilton, 2006) and elsewhere (Clement et al., 2009) have also documented the serious difficulty for GCMs in simulating the response of the large-scale cloud fields to interannual climate fluctuations (such as those associated with the El Niño phenomenon). It is difficult to put much credence in the cloud-climate feedbacks from models that do such a poor job of simulating the basic cloud climatology.

Progress in simulating cloud-climate feedbacks in GCMs may be achieved in various ways: improve-

ments in conventional subgrid-scale physics parameterizations; development of models in which conventional parameterizations are replaced with embedded cloud-resolving components, the so-called “super-parameterization” approach; and development of models with very fine, explicit resolution over the whole globe. Unfortunately, it will likely be sometime in the next decade before we have genuinely cloud-resolving global models.

Recently my colleagues and I at the IPRC have taken another approach; we have been evaluating the cloud-climate feedback in a regional atmospheric model with realistic imposed boundary conditions. These new results are discussed in the following story in this issue.

#### References

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