U.S. Senate Committee on Commerce, Science, and Transportation

Hearing on 'The Case for Climate Change Action'

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1. Introduction:

Projections of future climate change made using state-of-the-art climate models suggest that changes over the coming century will be much larger than experienced over the past 100 years. The case for taking action to mitigate these human-induced (or 'anthropogenic') changes rests on the credibility of these models. There is a vast scientific literature on the development and testing of these models, summarized in the recent 'Third Assessment Report' (henceforth 'TAR') produced under the auspices of Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC, Houghton et al., 2001). There are two main methods of model testing – comparing model simulations of the present state of the climate system (such as the geographical patterns of temperature, rain- and snowfall, sea-level pressure, etc.) against observations, and comparing model simulations of past changes in climate with observations.

The most recent climate models are able to simulate present-day climate remarkably well – with errors often less than the uncertainties in observational data sets. Here, however, I will not dwell on this aspect of model validation, but concentrate on the second method – comparison of observed and model-simulated changes. I will show that models simulate temperature changes over the past 100+ years with considerable fidelity provided they are driven (or 'forced') by observed changes in both natural forcing agents (such as variations in the output of the Sun) **and** anthropogenic factors (such as changes in greenhouse gas concentrations and aerosol particle changes). Natural forcing factors alone cannot explain the past record.

Using the results from this model/observed data comparison, I will give projections of future changes in global-mean temperature for a central scenario for future emissions. These results, which are consistent with projections given in the IPCC TAR, imply, for this particular emissions scenario, a future warming rate of three to five times the warming that occurred over the 20th century. The uncertainty range expands to two to seven times the past warming rate when emissions and other uncertainties are accounted for. Even at the low end, these projections are cause for concern.

Temperature changes over the 20th century:

The simplest indicator of climate change is the global-mean, near-surface temperature – the average over the Earth's surface area of temperature observations obtained primarily for the purposes of weather forecasting. After carefully correcting these data for instrumental and exposure changes, global-mean temperature shows a warming trend of about 0.7°C over the past 100 years. This warming trend has, superimposed on it, substantial variability on monthly, annual and decadal timescales associated with natural climate processes such as El Nino and other interactions between the land, ocean and cryosphere (ice) – see Figure 1.

To understand the causes of the century timescale warming trend we make use of climate models. Such models are an efficient way to synthesize and integrate, in an internally-consistent way, the many complexities and interactions of the climate system. The basic procedure begins by defining, independently of the model, the changes in the external drivers of the climate system. We then use these drivers as input forcing factors for the model and run the model to see how well it agrees with observed changes. In doing so, we try to quantify any uncertainties in both the inputs and the model structure to see what affects these uncertainties might have on the model outputs.

The forcing factors are of two types: natural agents like the effects of large volcanic eruptions and changes in the energy output of the Sun; and a variety of anthropogenic factors. Volcanic eruptions have a strong short-term cooling effect (Robock, 1999), and only a minimal effect on decadal or longer timescales. Since the goal here is to understand the century timescale warming, I will not consider volcanic effects further in this analysis, beyond noting that climate models are able to simulate the short-term coolings well. For changes in solar output, I use the recent estimates of Foukal (2002) from 1915 onwards and Hoyt and Schatten (1993) prior to 1915. Other estimates of solar output changes yield similar results. I do not consider the hypothesized amplification of solar forcing through the effects of cosmic rays, partly because there is no credible physical basis for this amplification. I note, however, that any assumed amplification of solar forcing degrades the agreement between model and observed results.

The anthropogenic factors include changes in the concentrations of greenhouse gases (carbon dioxide, methane, nitrous oxide, ozone, and various man-made halocarbons, of which the CFCs – chlorofluorocarbons – are the most well known), and changes in the atmospheric loading of small particles (aerosols) associated primarily with fossil-fuel burning. The greenhouse gases, of which carbon dioxide is the most important, have a warming effect. Aerosols, depending on type, may have either a warming or cooling effect. To date, the cooling effect dominates, but the magnitude of this cooling is still uncertain. In the results below I consider a range of possible values for the magnitude of aerosol cooling.

For the climate model I use the model employed by IPCC to produce their global-mean temperature projections (see Wigley and Raper, 2002, and references therein). This is a relatively simple model, but it has been rigorously tested against much more complex coupled Atmosphere/Ocean General Circulation Models (AOGCMs) and is able to simulate the results of these models with high accuracy over a wide range of conditions (Raper et al., 2001).

The simpler model has the advantage that it can be used to examine the effects of uncertainties in the parameters that control the response of the climate system to external forcing. The primary source of uncertainty is the 'climate sensitivity' parameter (designated by 'S' below). This is usually characterized by the eventual (or 'equilibrium') global-mean warming that would occur if we doubled the amount of carbon dioxide in the atmosphere. It has an uncertainty range of 1.5ºC to 4.5ºC with about 90% confidence. I will give results for sensitivity values of 2ºC and 4ºC to show the importance of this factor. For more information on sources of modeling uncertainty, see Wigley and Raper (2001).

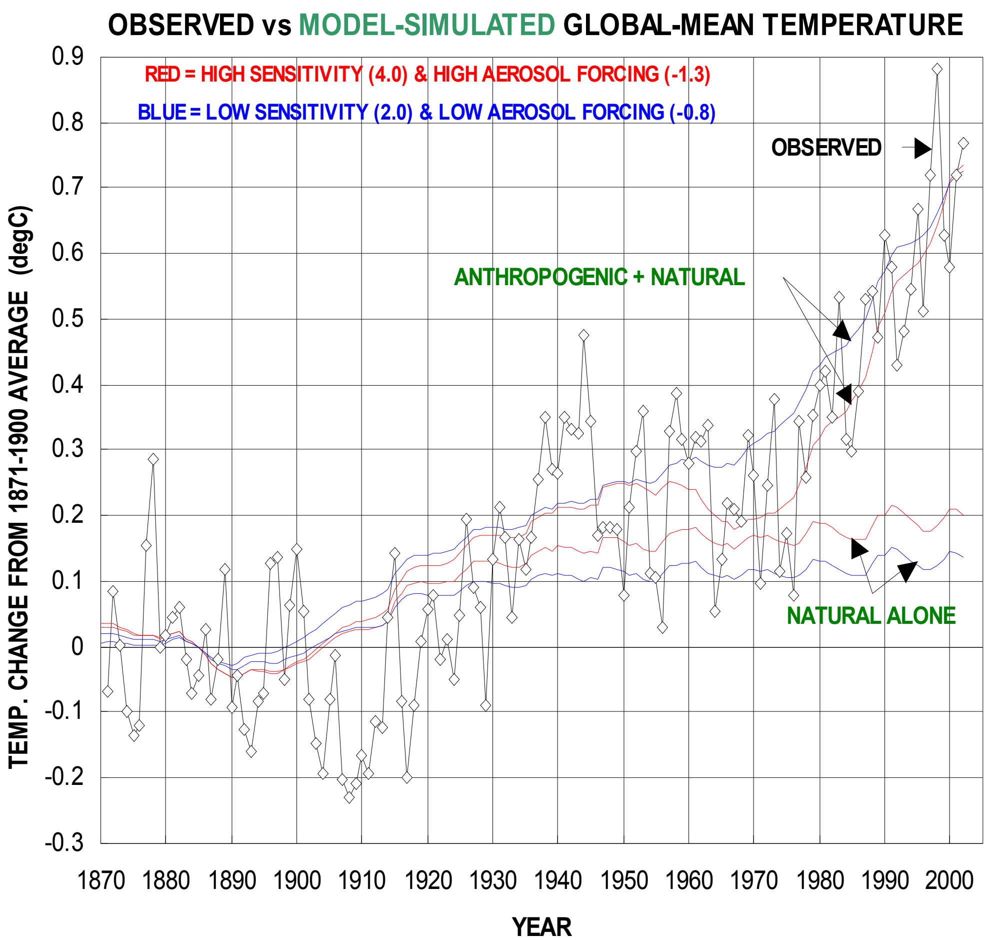

Figure 1: Observed versus model-simulated changes in global-mean, near-surface temperature. For observed data, see Jones et al. (1999) and Jones and Moberg (2003).

Figure 1 compares observed near-surface temperature changes with model predictions. The four model-based curves consider two forcing cases; one in which the model is driven solely by the primary natural driving force, changes in the output of the Sun (lower two curves), and one where both natural and anthropogenic forcings are used to drive the model (upper two curves). The two curves for each case reflect the main sources of uncertainty in the modeling exercise, the magnitude of aerosol forcing, and the magnitude of the climate sensitivity.

The upper two curves show that it is possible to obtain a good match between the model and observations by using a low aerosol forcing (–0.8W/m^2 in 1990) combined with low climate sensitivity (S = 2.0^{o}C), or by using a relatively high aerosol forcing (–1.3W/m^2 in 1990) combined with low climate sensitivity (S = 4.0^{o}C). Since these values are within their accepted ranges of uncertainty, it is clear that there is no inconsistency between models and observations. The observations, however, do not narrow the ranges of uncertainty for these two parameters, so, in making projections of future change, we need to account for these uncertainties.

The lower two curves show the expected global-mean temperature changes in the absence of anthropogenic forcing. Up to around the mid 1970s both the natural-forcing-only and the natural-plus-anthropogenic forcing cases fit the observations reasonably well. After this, the natural-only case provides an increasingly bad fit, while the natural-plus-anthropogenic case fits the observed warming trend extremely well. It is clear from this that anthropogenic forcing effects must be considered in order to explain the observations.

Satellite-based temperature changes since 1979:

One of the more puzzling aspects of recent climate change has been the apparent inconsistency between the linear trends in tropospheric temperatures (from satellite-based Microwave Sounding Units – MSU data), surface air temperatures, and model results (National Academy of Sciences (NAS), 2001). The original MSU data (see Christy et al., 2003, and earlier references cited therein – this data set is referred to below as the UAH data, since its developers are associated with the University of Alabama at Huntsville) showed little or no warming trend since the beginning of the satellite record in 1979, while both the surface data and model results for the surface and for the troposphere (as illustrated in Figure 1) showed a substantial warming trend. The NAS (2001) report concluded that there was no reason to suspect serious errors in any of the trends, but this rather down-played what is really an important inconsistency.

More recent work has moved towards resolving this inconsistency. First, an entirely independent analysis of the raw satellite data (the MSU2 data specifically) has recently been carried by Mears et al. (2003 – these authors are with Remote Sensing Systems, Santa Rosa, CA, so their data set is referred to below as the RSS data). This new analysis has a warming trend that is both larger than the UAH trend and more consistent with both the surface and model data (Santer et al., 2003a). Second, a new reanalysis product (the ERA-40 data produced by the European Centre for Medium-range Weather Forecasting), when used to construct equivalent MSU2 temperature trends, also shows a larger warming trend than the UAH data. (Reanalysis is a technique for synthesizing diverse observational data sets, including both satellite and radiosonde data, to produce an internally-consistent picture of changes in atmospheric meteorological conditions – the ERA exercise is described in Gibson et al., 1997.) Third, analysis of changes in the height of the tropopause – the boundary between the lowest layer of the atmosphere, the troposphere, where temperatures decrease with height, and the layer above this, the stratosphere, where temperatures either change little or increase with height – show that these changes can only be explained if the troposphere is warming (Santer et al., 2003b).

Trends in the three observed data sets, UAH, RSS and ERA-40 are shown in Figure 2, along with model results consistent with those shown in Figure 1. The observed trends have substantial statistical uncertainty because of the 'noise' of inter-annual variations about the underlying trend. The statistical uncertainty ranges shown in the Figure are the 'two-sigma' ranges, corresponding to 95% confidence intervals. For the model results there are additional uncertainties associated primarily with radiative forcing and climate sensitivity uncertainties, as explained above.

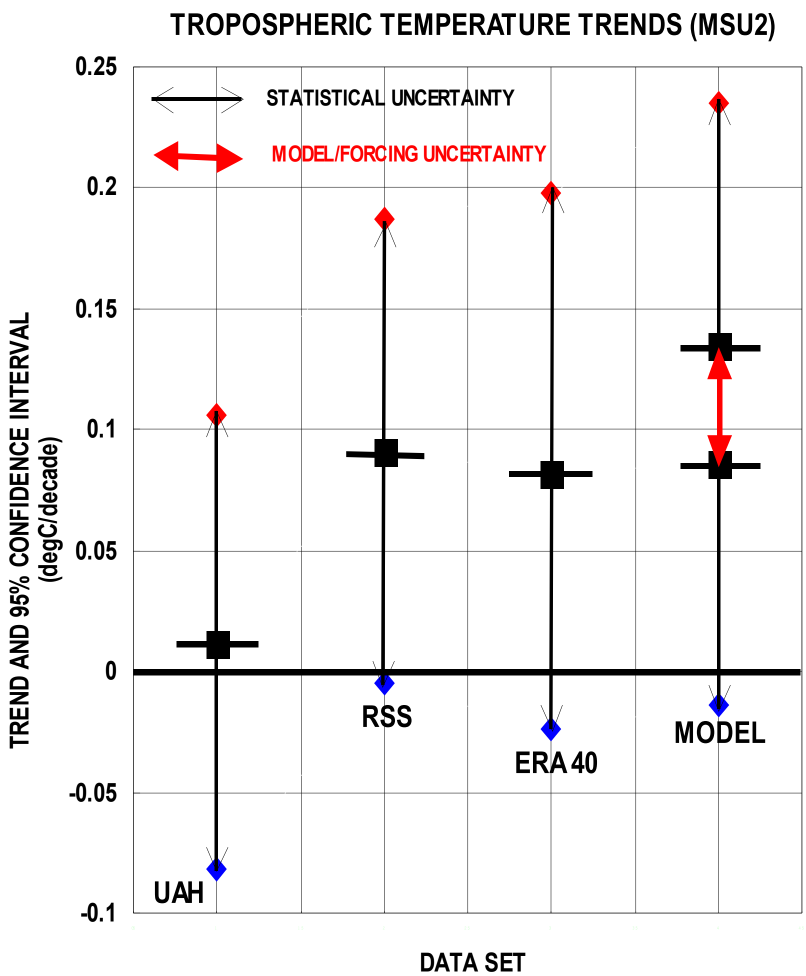

Figure 2: Trends over 1979–2001 and trend uncertainties for different tropospheric data sets.

In a statistical sense, Figure 2 shows that there is no significant difference between any of the trends. While it is clear that the UAH results are qualitatively different from the other results, because of the uncertainties involved it is too soon to pass judgment. As noted by Santer et al. (2003a), model results cannot be used as a basis for selecting one observed data set over another. The key result of this comparison is that it exposes uncertainties that are larger than hitherto suspected. If, however, the UAH data are found to have underestimated the warming trend in the troposphere, then this will resolve an important climatological ‘problem’ and provide a strong endorsement for the validity of current climate models.

Supporting evidence for 20th century climate change:

The temperature results above provide strong evidence for the reality of a strong warming trend over the 20th century. The warming is consistent with model expectations and can only be explained if one includes anthropogenic factors as part of the cause. From Figure 1, the natural warming trend over the 20th century accounts for only 23–32% of the total trend. The observations are also consistent with a climate sensitivity in the standard 1.5°C to 4.5°C range, and are not consistent with a lower value.

These results are consistent with many other lines of evidence that there are unusual changes occurring in the climate system. Not only are global-mean temperature changes consistent with models, but the horizontal and vertical patterns of change also agree with model predictions (TAR). In addition, a sharp cooling trend has been observed in the stratosphere that agrees well with model predictions (Santer et al., 2003a). Sea level has been rising steadily (TAR), partly as a result of warming in the ocean that agrees with model expectations (Barnett et al., 2001) and partly due to the melting of glaciers and small ice sheets (TAR). Sea ice area and thickness have also been decreasing in accord with the changes suggested by models (Vinnikov et al., 1999). Sea-level pressure patterns have shown significant changes and, once again, these changes are similar to those predicted by models (Gillett et al., 2003). The frequency of precipitation extremes has also been increasing (Karl and Knight, 1998; Groisman et al., 1999), a result that agrees both with simple physical reasoning (Trenberth et al., 2003) and with model predictions (Wilby and Wigley, 2002). Finally, based on paleoclimatological evidence, the warmth that characterizes the late 20th century is, at least for the Northern Hemisphere, unprecedented in at least 1000 years (Mann and Jones, 2003).

Climate change over the 21st century:

Given the weight of evidence endorsing the credibility of climate models, at least at large spatial scales, we can safely use these models to estimate what changes might occur over the next 100 years. To do this we must first estimate how the emissions of all climatically-active gases will change in the future. As part of the IPCC Third Assessment Report process, a large set of future emissions scenarios was developed, all under the ‘no-climate-policy’ assumption (referred to as the ‘SRES’ scenarios for ‘Special Report on Emissions Scenarios’; Nakićenović and Swart, 2000). In total there are 35 complete scenarios spanning a range of assumptions about future population growth, economic growth, technological change, and so on – and each set of assumptions leads to a different set of emissions. In order to predict future climate one must take account of the attendant uncertainties in emissions, since it is these that drive changes in the composition of the atmosphere, which in turn drive changes in the climate system. At each step, in going from emissions to atmospheric composition changes, and from composition changes to climate, there are other uncertainties that must be taken into account. Most of these uncertainties were accounted for in the TAR, where the estimated changes in global-mean temperature over 1990 to 2100 were given as 1.4ºC to 5.8ºC. A more formal probabilistic analysis was given by Wigley and Raper (2001).

Here, to illustrate the procedure, I will use a single emissions scenario, the A1B scenario, which is roughly in the middle of the range covered by the SRES set. I will then account for uncertainties in aerosol forcing and climate sensitivity as in Figure 1 (recognizing that this does not span the full range of uncertainties in these parameters). The projected future changes in global-mean temperature, compared with past changes, are shown in Figure 3.

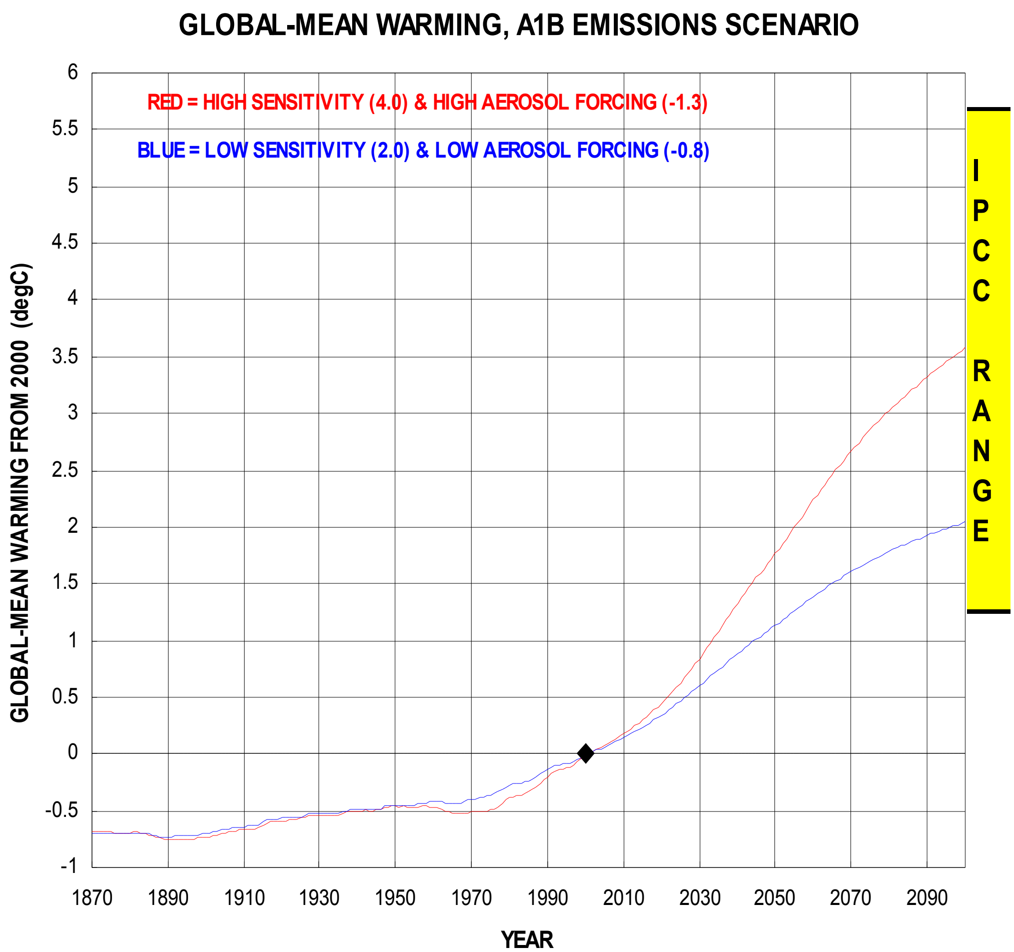

Figure 3: Projected global-mean warming.

Over 2000 to 2100 the warming range is 2.0ºC to 3.6ºC, which corresponds to warming rates of roughly three to five times the rate of warming over the 20th century – and temperatures are still increasing at the end of the century. A wider uncertainty range is obtained when other uncertainties are accounted for, as in the TAR analysis (shown by the bar on the right side of the Figure). Even at the low end of the range of possibilities, the warming rate over 2000 to 2100 is double the 20th century warming rate, while at the top end the future rate is seven times the past rate.

Major changes in all aspects of climate will occur in parallel with these unprecedented global-mean temperature increases. Many of these will be beyond our present adaptive capabilities (particularly in lesser developed countries), and will undoubtedly lead to damages to natural ecosystems and managed systems such as agriculture and water resources, and to possibly serious consequences for health and the spread of pests and disease. While the changes and their impacts cannot be predicted in detail, and while some of the consequences of future climate and atmospheric change may be positive, it would be prudent to insure against adverse changes either through improving our adaptive capabilities and/or, through emissions mitigation, reducing the magnitude of future climate change. In the absence of climate policies, as time goes by we will be moving further and further into unknown climate territory and committing ourselves to even larger future changes. Because of the inertia in both socioeconomic systems and the climate system, it is likely that quite aggressive actions may be required to avoid (quoting Article 2 of the Framework Convention on Climate Change) 'dangerous interference with the climate system', and ensure that we are able to stabilize the composition of the atmosphere and the climate at acceptable levels.

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