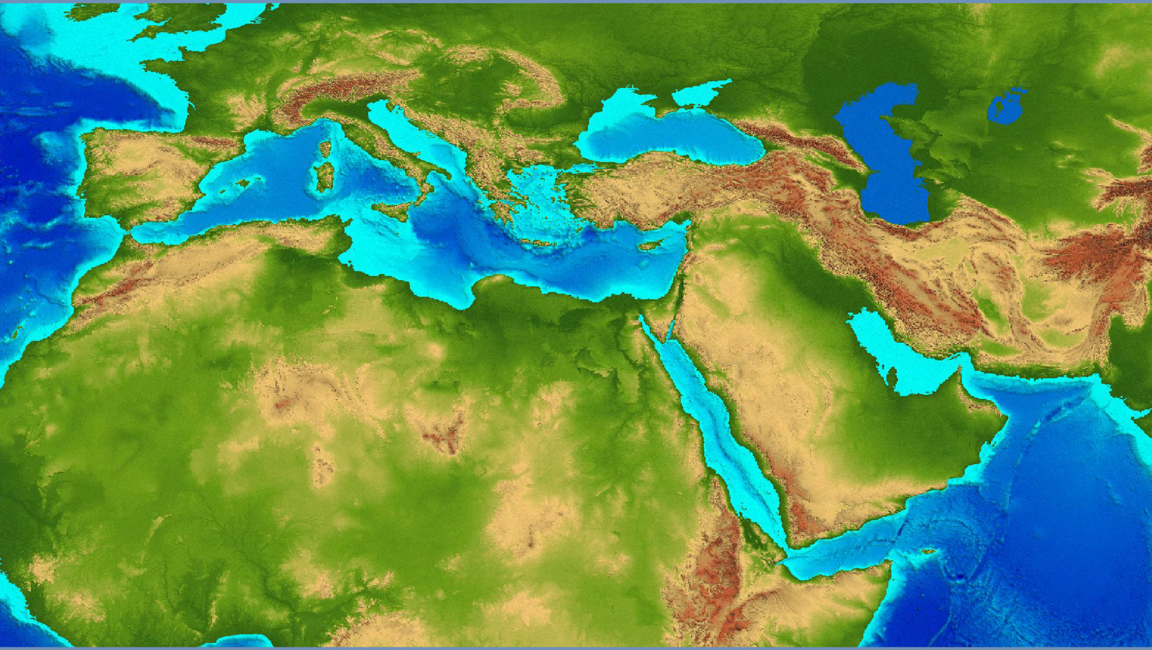
Ambient Air Pollution



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Chapter 5

Global Warming and Climate Change: State of the Science

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Abstract: A broad base of measurements supports the fact that the earth's average temperature is warming, i.e. that warming is a global event. Warming trends are consistent between both hemispheres between surface measurements and those of the entire lower troposphere by satellites.

Attribution of the warming to increased greenhouse gas concentration is still uncertain. Values of climate forcing aside from that due to well-mixed greenhouse gases is still highly uncertain. In addition, Atmosphere-Ocean General Circulation Models (AOGCMs) are still problematic - many important feedback processes (most notably those associated with clouds) are parameterized, and they still produce better predictions when using artificial "flux-adjustments".

Keywords: Global warming, Climate change, Atmosphere-Ocean General Circulation Models, AOGCM, Greenhouse gasses.

1 Introduction

The possibility of global warming and associated climate change resulting from industrial greenhouse gas (GHG) emissions is one of the most important environmental problems of the last twenty years. This paper reviews this question by addressing its two central issues:

1) Is the earth warming? If so, is the warming representative of a global-scale event, i.e. can it truly be considered "global warming"?

2) If global warming is occurring, can the cause of it be attributed to increased greenhouse gas concentrations?

Since climate change (for example, increased hurricane strength) is assumed to follow from global warming, our focus here is on global warming. We will review the current state of science and offer our opinions on the issue. In particular, we discuss the accuracy of Atmospheric-Ocean General Circulation Models (AOGCM), which are used to attribute the cause of global warming as well as to make climate projections based on various future scenarios of GHG emissions.

2 Background

Greenhouse gas concentrations have increased over the last century. These concentration increases have occurred alongside long-term monotonic increase in emissions. Time trends of carbon dioxide (CO_2) emissions and concentration over the last century (Figure 2-1 and 2-2) illustrate this increase. Additional plots showing longer period trends in CO_2 from "proxy" measurements, most importantly Antarctic ice-cores, show that this increase started in the late 19^{th} century, at the time when anthropogenic industrial activity and burning of fossil fuels began in large scale (Figure 2-3). It is now the strong consensus that the increase in GHG concentrations is due to increased industrial emissions.

It is also well-known that greenhouse gases in the atmosphere act to warm the earth-atmosphere system. This happens due to the absorption and reemission to the surface of surface-emitted infrared radiation by these gases. Less upward radiation therefore leaves the planet than would otherwise be the case without greenhouse gases in the atmosphere, thereby keeping the earth warmer than it otherwise would be. The most abundant naturally occurring greenhouse gas in the atmosphere is water vapor. CO_2 is second, but it is the most abundant GHG of anthropogenic origin.

The global-warming hypothesis therefore follows from inferring that the increased GHG concentrations over the last century will further warm the planet above and beyond that which is already occurring naturally, and that this warming will be detrimental to the earth's climate system and its ability to support life. The two questions are must be answered to determine if the first part of this is true.

A couple of issues must be considered in addressing these two questions. In answering the first, one is faced with discerning, among other things, regional warming from global-scale warming. A multitude of measurements around the world, in both hemispheres, at different altitudes and over many different surfaces would thus be needed. In answering the second, one is faced with discerning natural climate variability from anthropogenic variability, as well as with discerning the effects on warming of anthropogenic processes aside from increased GHG emissions from those due to these emissions. This task is further complicated by the existence of many processes that occur *as a result of* warming due to increased GHG concentration, i.e. the climate "feedbacks". These feedbacks can either amplify or suppress the original warming due to GHG forcing.

We will make use of many plots presented by the International Panel on Climate Change (IPCC) in this presentation. The IPCC was formed by the United Nations Environment Programme and World Meteorological Organization to investigate the climate change problem, and represents what most consider a scientific "consensus" on the issue[1].

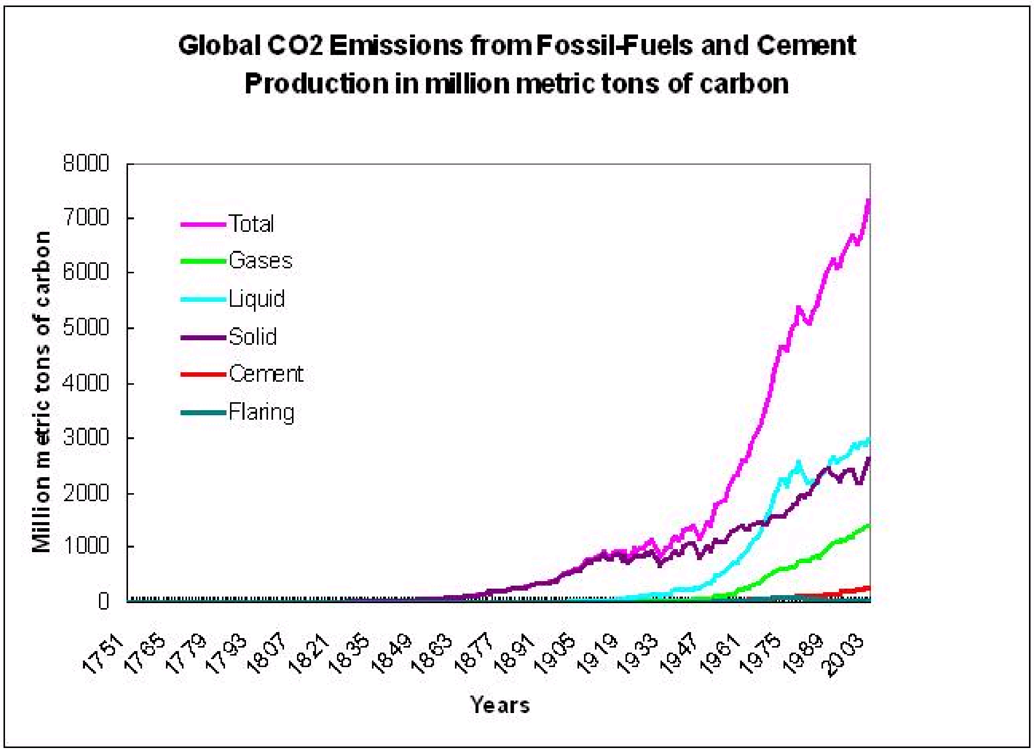

Figure 2-1: Estimated anthropogenic emissions of carbon dioxide (CO_2) emissions over time. Graph taken from http://cdiac.ornl.gov/trends/emis/em_cont.htm (see electronic book for full color version).

[1] See http://www.ipcc.ch for full details about the IPCC.

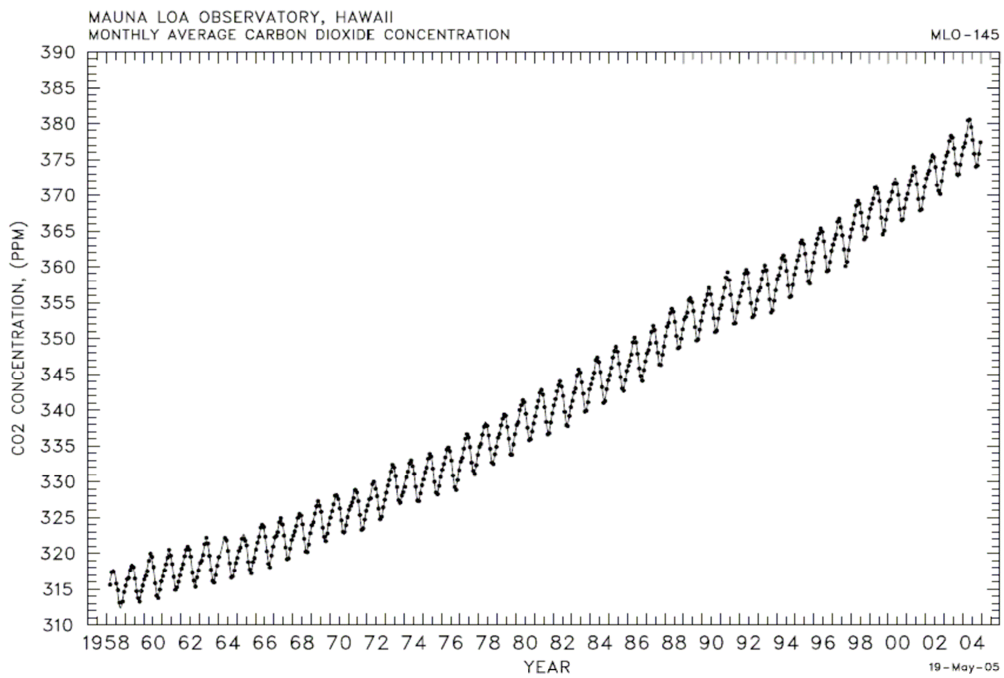

Figure 2-2: Concentrations of atmospheric concentrations of carbon dioxide (CO_2) at the Mauna Loa observatory in Hawaii. Taken from http://cdiac.ornl.gov/trends/co2/sio-mlo.htm .

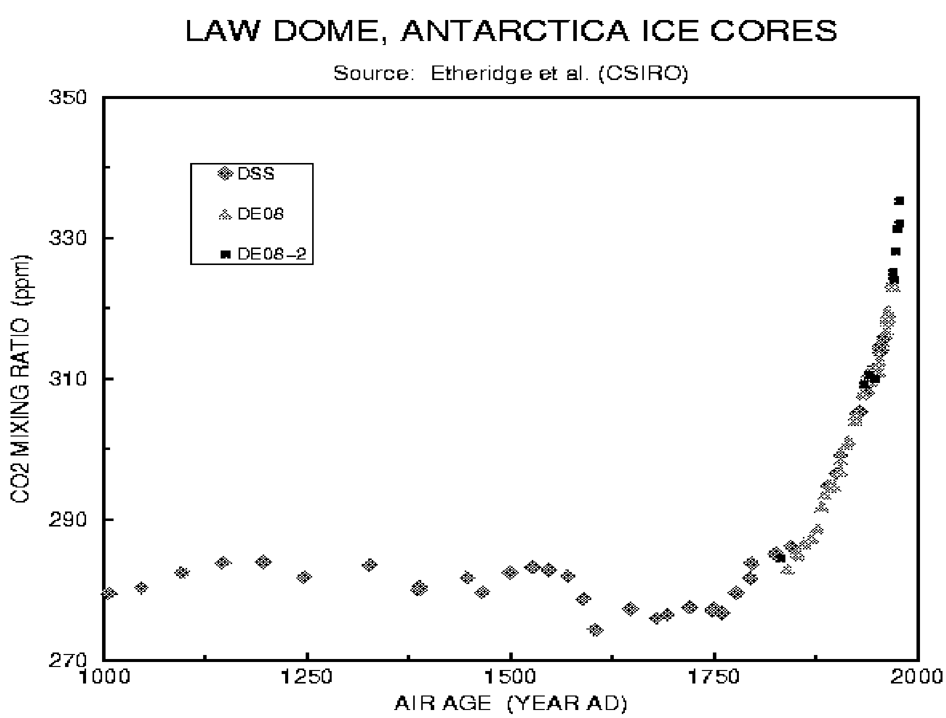

Figure 2-3: Carbon dioxide (CO_2) concentrations measured from ice core samples taken from Law Dome, Antarctica. Taken from http://cdiac.ornl.gov/trends/co2/contents.htm.

3 Do Measured Increases in Temperature Represent Global Warming?

Direct measurements of surface temperature exist since approximately the middle part of the 19th century. These include land surface temperature (LST) and sea surface temperature (SST); the latter measured from bucket samples aboard ships and from thermometers aboard buoys. Satellite measurements of SST have also become available over the last approximately 25 years. Above the surface, satellite measurements of the entire lower atmosphere (troposphere and stratosphere) have become available over the last 25 years. Consistency of surface and lower atmospheric temperature trends is expected on physical grounds. Finally, "proxy" records of temperature trends over the last 1000 years are available from ice cores, tree rings, corals and boreholes. Although more uncertainty exists in these, taken collectively they allow a longer time-period of the earth's temperature to be obtained than is possible with direct surface and satellite measurements. This then gives a better check of whether any global warming over the last century deduced over the last century from direct measurements is unusual with respect to natural variations over the last thousand years.

(a) Surface Measurements

Surface temperature anomalies from the middle 19th century to current-day relative to the 1960-1991 average are shown in Figure 3-1. A warming trend is evident in both hemispheres of similar value of approximately +0.06 ºC per decade between 1900 and 2000. The fact that both hemispheres exhibit similar values indicates that the warming is a global event. It is emphasized that effort has been made to screen the LST record for urban bias, yet a portion of the standard error is nonetheless attributed to urban biases. A more detailed analysis quantifies urban warming as approximately 10% of the total LST increase[2]. One can also see that the warming is not uniform in time, but rather occurs mainly during two time periods: 1910-1940 and 1980-current.

(b) Satellite Measurements

Average temperatures of the earth's lower atmosphere (the troposphere and stratosphere, comprising roughly the lowest 25 km of the atmosphere) have been measured by satellites since the late 1970s. The advantage of such measurements is their geographic coverage – they cover the entire globe horizontally as well as the entire lower atmosphere vertically – which makes them especially valuable to detect global-scale warming. The technique of relating microwave emissions (from atmospheric oxygen) to temperature, however, involves a series of calibrations and corrections, which have evolved in accuracy over the years. This

[2] http://www.grida.no/climate/ipcc_tar/wg1/052.htm#2221

must be considered when interpreting the value of warming deduced from satellites reported at a given time.

Up until recently, satellites have consistently shown considerably less warming than surface observations. In recent years, however, it has been found that one of the corrections needed for processing the satellite microwave emissions has been applied incorrectly. The problem has since been corrected, although in different ways by the two main groups involved in taking and processing satellite data (UAH and RSS). As a result of these corrections, the UAH group arrives at a value of recent warming (since around 1980) of about 0.12ºC per decade, which is much closer to surface observations than previously calculated, while the RSS group arrives at a value of about 0.19 ºC per decade, which is very close to the surface warming rate since 1980. A greater degree of consistency is therefore now found between surface and satellite observations[3].

(c) Proxy Records

A longer time period of temperature change than from direct measurements can be obtained from "proxy" measurements. These include measurements of tree-ring width and density, geochemical properties of ice cores, sea/lake sediments and corals, and temperature variations with depth from boreholes. From this collection, a record of temperature has been constructed for roughly the last 1000 years, restricted mainly to the northern hemisphere. Several uncertainties exist in these measurements and/or their ability to be used to deduce large-scale climatic change. These can be associated with the methodology of relating temperature to the direct variable sampled from the proxy, lack of spatial coverage over the entire hemisphere and uniqueness to a specific surface (land or sea). For this reason, it is important to view the trends from proxies collectively, rather than focusing on the trend from a particular type of proxy[4].

Reconstructions of northern hemisphere temperature anomalies over the past 1000 years from proxy records are shown in Figures 3-2 and 3-3. The graphs depict two major features. First, temperatures over the last twenty years are warmer than at any time over the last 1000 years. Second, the warming rate experienced over the last century is higher than at any time over the last 1000 years. Although there are century-scale periods of warming or cooling during the last 1000 years (discussed below), the rates associated with these periods are modest compared to the last century. For this reason, this reconstruction is often termed the "hockey stick", with the "stick" representing the pre-20th century period and the "blade" the trend during the 20th and into the 21st century.

Obviously, the term "hockey stick" is an idealization that belies the fact that important temperature variability has, in fact, occurred before the 20th century.

3 See http://www.realclimate.org/index.php/archives/2005/08/et-tu-lt/ for further details and references to journal literature detailing this issue.

4 See http://www.grida.no/climate/ipcc_tar/wg1/068.htm for further details on proxies.

Particularly, the period of about 1000-1400 comprised a warm period (the "Medieval Warm Period") and the period of about 1500-1900 a cold period (the "Little Ice Age"). This is more visible in Figure 3-3. The temperature assigned to these periods depends greatly on the type of proxy. Also, research suggests that the "Little Ice Age" probably was not a global-scale event, but rather characterized by two distinct periods - the 16th century with the cooling concentrated over Europe and the North Atlantic, and the 19th century with the cooling concentrated over North America. This may be why boreholes, since they are concentrated in the North Atlantic area, tend to suggest a colder "Little Ice Age" than that deduced from the proxies taken together. Nonetheless, the precise temperature trend of the past 1000 years is yet to be resolved, and important debate about proxy measurements continues[5].

(d) Summary

Based on measured temperature trends, global temperatures of current day are warmer than at any time over the last 1000 years. The uniformity of the warming over both hemispheres, over land and ocean, and throughout the troposphere indicates that the warming is a global event.

Although not discussed above, reduction of land ice and snow cover, polar ice sheets, as well as rises in ocean sea levels and heat content that have been observed over the last decades are consistent with increased global temperatures. This adds additional support for the determination that global warming is occurring[6].

Natural variation of temperatures has occurred over the last 1000 years. Specifically, temperature trends indicate a "Medieval Warm Period" over the period 1000-1400 and a "Little Ice Age" from about 1500-1900. This rate of variation associated with these events is less than the amount of warming experienced over the last couple decades. In addition, these events appear to be regional, affecting North America, the North Atlantic and Europe at different times within the periods.

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[5] Further details on the "Medieval Warm Period" and "Little Ice Age" can be found at http://www.grida.no/climate/ipcc_tar/wg1/070.htm .

[6] See http://www.grida.no/climate/ipcc_tar/wg1/408.htm as well as Hanson, J. and coauthors, 2005: "Earth's Energy Imbalance: Confirmation and Implications", *Science*, 308, 1431-1435.

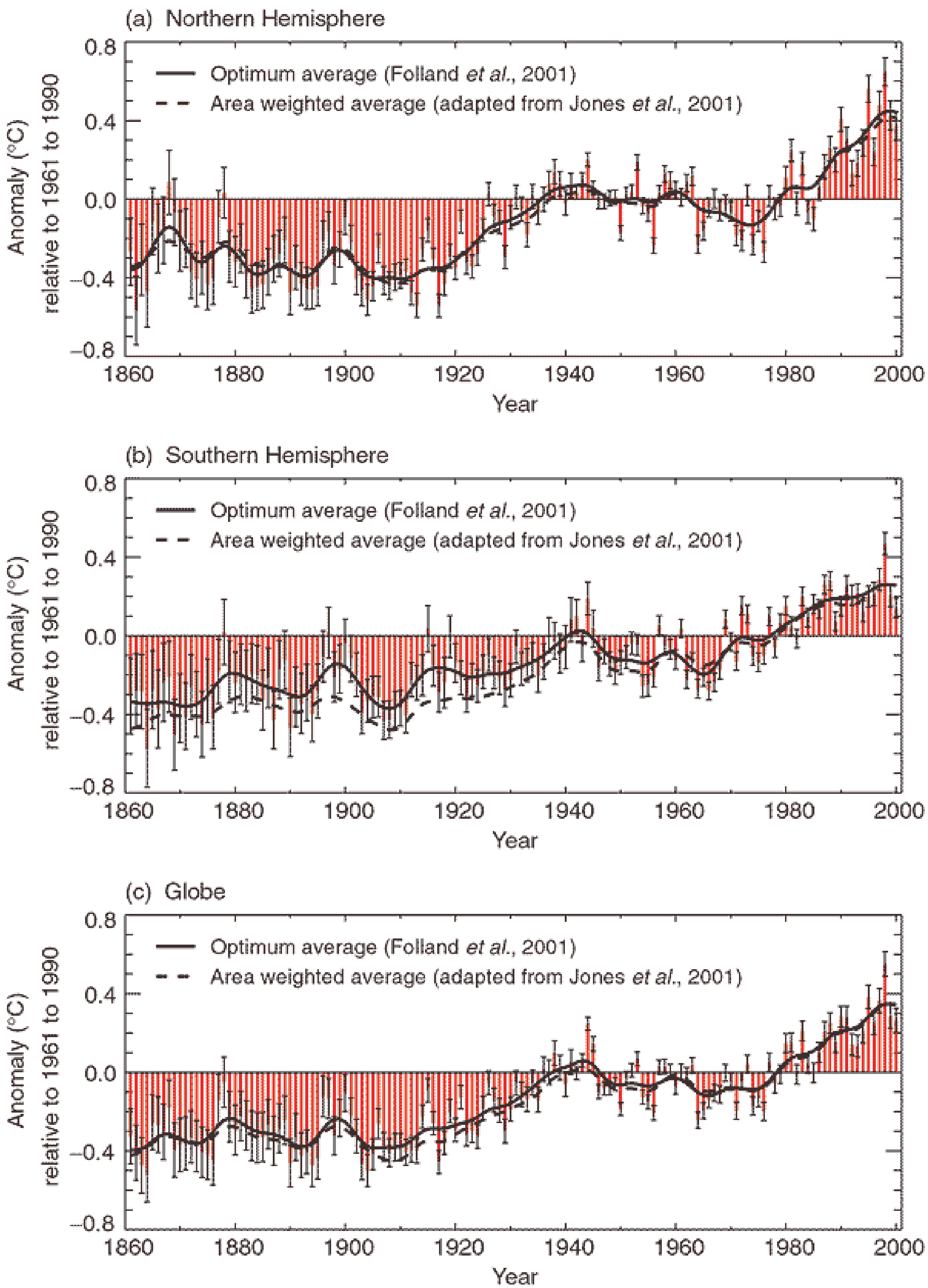

Figure 3-1: Average combined land-sea surface temperature anomalies. Taken from http://www.grida.no/climate/ipcc_tar/wg1/056.htm.

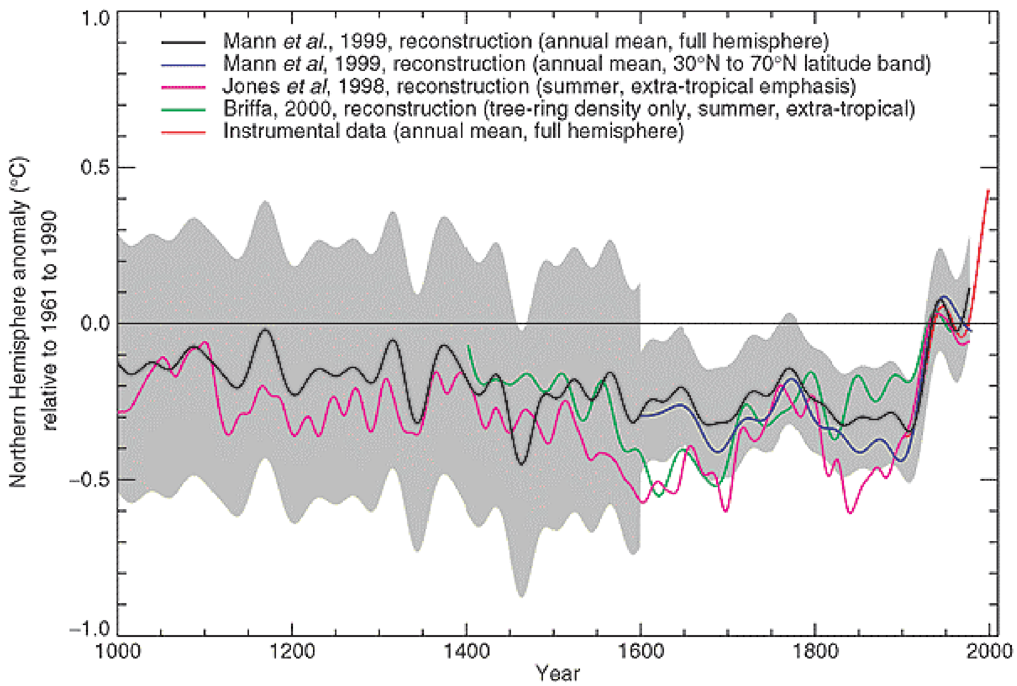

Figure 3-2: Northern hemisphere surface temperature anomalies relative to 1961-1990 average. Taken from http://www.grida.no/climate/ipcc_tar/wg1/069.htm#2322 **(see electronic book for full color version).**

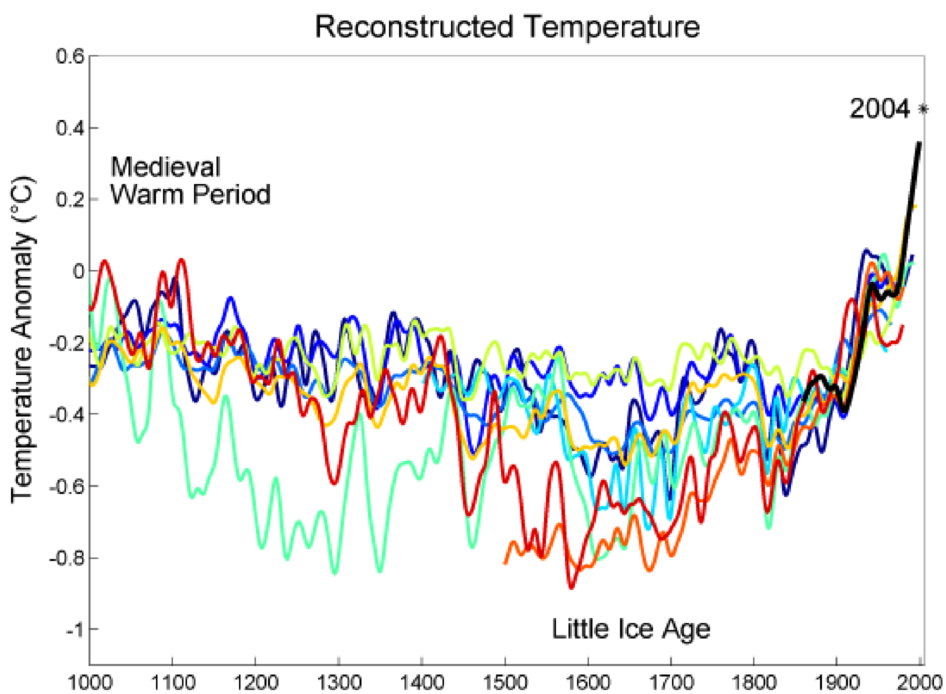

Figure 3-3: As Figure 3-2. The individual lines are reconstructions based on the work of different authors, see http://www.realclimate.org/index.php/archives/2005/02/moberg-et-al-highly-variable-northern-hemisphere-temperatures/ **for details (see electronic book for full color version).**

4 Can Global Warming Be Attributed to Increased GHG Concentrations?

In this section, the question of whether global warming can be attributed to increased GHG concentrations is addressed.

The above question is a complicated one. This is first because increased GHG concentration is one of many forcings that must be accounted for in investigating the question. Others include changes in solar radiation intensity, changes in atmospheric particulate concentrations resulting from volcanic activity, increased concentrations of radiatively active pollutant gases and aerosols (e.g. ozone and sulfate particles) and land use changes. Second, any global temperature change due these forcings is also a result of *climate feedbacks*. A feedback is a process triggered by a change in forcing that itself has an effect on global temperature and climate.

Due to the myriad of forcings and feedbacks, it is practically impossible to separate the effects of them individually in real-world data to attempt attribution of the cause of global warming. This is instead done by computer models, in particular Atmospheric-Ocean General Circulation Models (AOGCMs).

a) Climate Forcing

Climate forcing is the change in net radiation induced on the earth-atmosphere system (more specifically, at the tropopause) that results from a change in some characteristic of the earth-atmosphere system. Since is defined for a single change, it must be calculated computationally (rather than deduced from observed data) since only then can one isolate the effects of a single change.

The values of climate forcing for various processes, as reported by the IPCC, are shown in Figure 4-1. Uncertainty bars as well as the degree of confidence for each forcing are also shown. GHG forcing is seen to be responsible for the majority of total positive forcing, accounting for roughly two-thirds of this total. Confidence GHG forcing is also seen to be "high". The most important negative forcing is due to tropospheric aerosols, which is divided into a "direct" and "indirect" component. The direct forcing is due to reflection of sunlight by the aerosols themselves, and the indirect forcing due to reflection by increased number of cloud drops (for constant liquid water content) induced by increased aerosol concentration. Collectively these represent a strong negative forcing, which offsets a large part of the GHG forcing. Confidence in the value of tropospheric aerosol forcing, however, is "low".

It is important to note that Figure 4-1 is for global-scale forcing and only due to the processes shown. In reality, forcing can vary strongly regionally. Forcing due to land-use changes, in particular, often leads to higher forcing values *regionally* than the small negative value ascribed to it globally in Figure 4-1. An obvious example of this is in urban areas, which are known to have strong "heat-island effects" due to replacement of a natural vegetated area with concrete. Another example is in the northern hemisphere winter and spring due to tropospheric ozone[7]. Another forcing, which has not been included in Figure 3-1, is nitrogen deposition[8]. Since temperature *differences* from place to place, rather than temperature itself, force atmospheric circulations, regional forcings may be more important in affecting overall climate change (i.e. weather circulations, hurricanes, etc …) than an overall increase in earth average temperature.

b) AOGCM Results

While climate forcing is a useful concept in comparing the various driving processes of global temperature change, the amount of actual temperature is only determined by combining the forcing with the climate feedbacks they introduce. As described above, feedbacks are the tropospheric response to forcing, and can either amplify or suppress the original forcing. This combined analysis of forcing and feedbacks is best carried out by the use of Atmospheric-Ocean General Circulation Models (AOGCM). AOGCMs are elaborate computer models that simulate earth's climate. The equations of AOGCMs are solved computationally forward in time to generate climate projections based on a prescribed initial climate. By running AOGCMs, scientists attempt to determine whether the cause of global warming is increased GHG concentration.

Most current AOGCMs contain equations to represent essentially all of the important forcing-feedback interactions of the earth climate system in one way or another. In fact, as will be seen below, they are successful in reproducing most of the basic features of the earth climate pattern. Important problems, however, exist in AOGCMs. The two main ones in our view are as follows:

1. Since the model equations are solved only at a finite number of locations and vertical levels of the atmosphere, processes that occur on scales finer than the model grid must be "parameterized". Equations involved with parameterizations are highly uncertain, and many important climate feedbacks (especially cloud processes) are heavily parameterized in AOGCMs.

2. AOGCMs still, in general, necessitate "flux-adjustments" to enable stable climate projections. Flux-adjustments are "artificial" forcings, most often imposed through the either alteration of the model-predicted ocean sensible heat or momentum fluxes, which do not relate to any specific physical process. Recently, some AOGCMs have improved to the point where flux-adjustments are not needed, however their climate projections, while stable, are generally not as accurate as those that use flux

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[7] See http://climatesci.atmos.colostate.edu/2006/03/14/another-major-non-co2-climate-forcing-of-global-warming/

[8] http://climatesci.atmos.colostate.edu/2005/10/10/is-nitrogen-deposition-a-first-order-climate-forcing/

adjustments (see below). Obviously, the need for flux adjustments limits the confidence in the use of AOGCMs for climate projections.

These problems are in addition to the high uncertainties in the values of many important climate forcings (which are inputs to AOGCMs), discussed in the previous section.

Composite results of several AOGCM simulations for mean sea level pressure and surface air temperature are shown in Figures 4-2 and 4-3, respectively. The results are for "control" simulations, i.e. without greenhouse gas or other anthropogenic forcing. It is seen that the simulations reproduce the basic expected surface pressure patterns, for example the equatorial low pressure belt, high pressure centers off the west coast of continents in the southern hemisphere, as well as the Aleutian and Icelandic low pressure and Siberian high pressure systems in the northern hemisphere. Temperature patterns are also fairly well predicted over most of the globe. The major areas of error can be seen to occur at high latitudes in both hemispheres, especially in the polar areas. Errors in precipitation (not shown) also occur in the equatorial region, especially over the western Pacific where there is underprediction of precipitation. It should be noted that models that both use and do not use flux adjustments are used in this composite. Non-flux adjusted models generally have greater errors than flux adjusted models, especially over high latitudes and off the west coast of continents, where cloud cover tends to be underpredicted by non-flux adjustment models[9].

The Surface temperature predictions of AOGCM simulations incorporating anthropogenic forcing (GHGs plus aerosols) versus those for "control" simulations are shown in Figures 4-4. It is seen that the surface air temperature warming experienced over the 20th century is predicted with far more accuracy when applying anthropogenic forcing. Ocean heat content increases over the 1990s are also seen to be captured in simulations with anthropogenic forcing (Figure 4-5). It is mainly because of this success that the IPCC has attributed the cause of the warming of the 20th century to increases in GHG concentrations.

Caution must be taken, however, when interpreting these AOGCM results. As discussed in the previous section, climate forcing due to processes aside from GHG is very uncertain. This is especially the case for tropospheric aerosols, without whose negative forcing AOGCMs would predict far more warming than observed. In addition, a large part of the warming is not directly due to GHG forcing but instead to the positive water vapor feedback it induces. However, cloud and subgrid convective mixing processes, which have important effects on vertically dispersing and removing water vapor in the atmosphere, are highly parameterized in AOGCMs. Furthermore, a large part of the warming geographically predicted by AOGCMs is located over Northern hemisphere mid-

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[9] Further details can be found in Lambert and Boer, 2001: "CMIP1 evaluation and intercomparison of coupled climate models", *Clim. Dyn.*, 17, 83-106.

and high latitudes during night and winter. The parameterization of stable boundary layer processes, which strongly control near-surface air temperatures in these regions, however, is another area of high uncertainty[10]. Use of flux adjustments in models also decreases the confidence in AOGCM predictions.

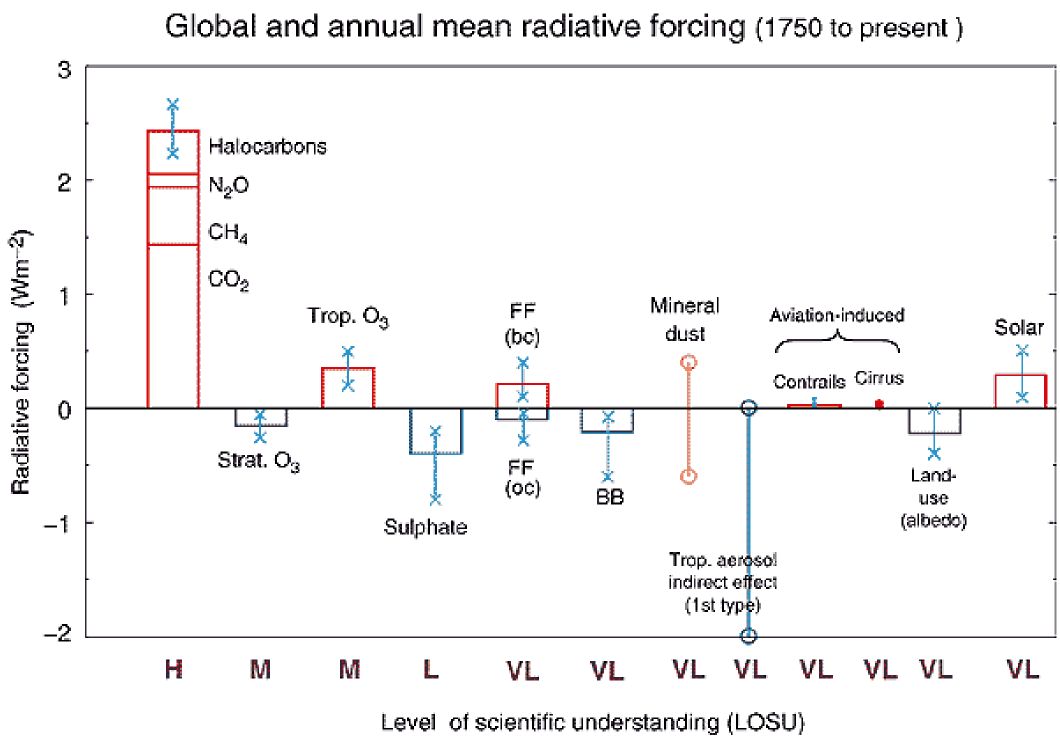

Figure 4-1: Values of climate forcing of the earth-atmosphere system due to various processes, as reported by the IPCC. See text for description, and http://www.grida.no/climate/ipcc_tar/wg1/251.htm for additional details.

[10] See http://climatesci.atmos.colostate.edu/index.php?s=GABLS

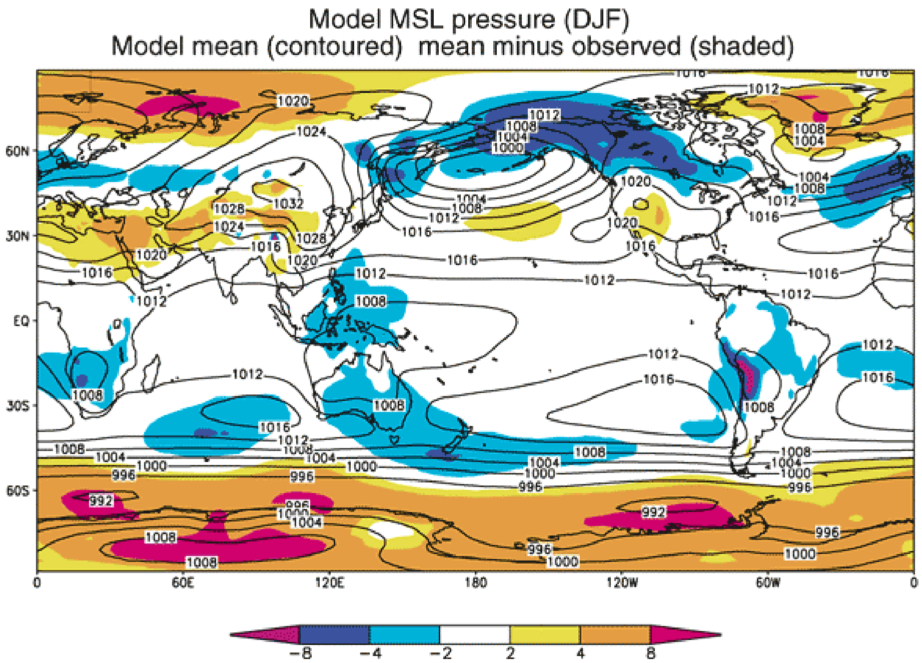

Figure 4-2: Modeled average December-January-February (DJF) mean sea level pressure and deviations from (estimated) observations. Results are averages of a suite of AOGCM models (see http://www.grida.no/climate/ipcc_tar/wg1/316.htm). Graph is taken from http://www.grida.no/climate/ipcc_tar/wg1/317.htm (see electronic book for full color version).

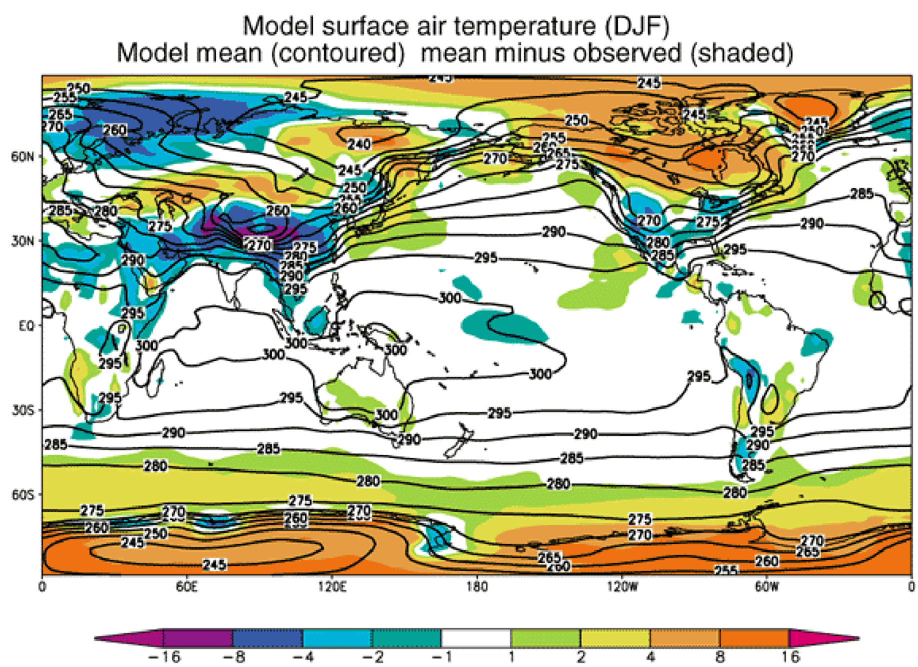

Figure 4-3: Modeled average December-January-February (DJF) surface air temperatures and deviations from (estimated) observations. Results are averages of a suite of AOGCM models (see http://www.grida.no/climate/ipcc_tar/wg1/316.htm). Graph is taken from http://www.grida.no/climate/ipcc_tar/wg1/317.htm (see electronic book for full color version).

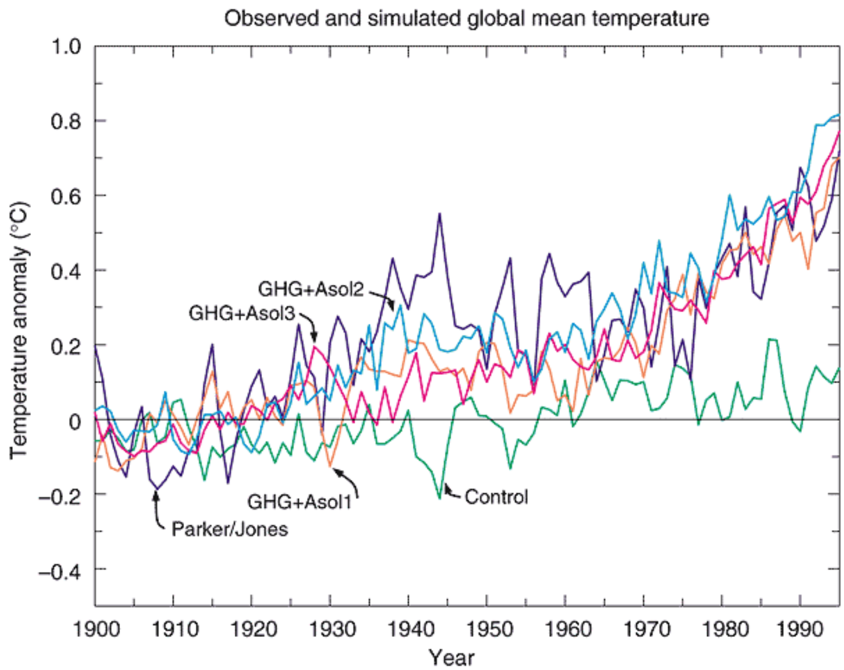

Figure 4-4: Temperature anomaly relative to 1960-1991 versus year for 'control' (black, entitled "Parker/Jones") and three greenhouse gas and anthropogenic emission forcing AOGCM simulations. The three GHG+Asol simulations are for three different initial conditions. Graph is taken from http://www.grida.no/climate/ipcc_tar/wg1/326.htm#861 (see electronic book for full color version).

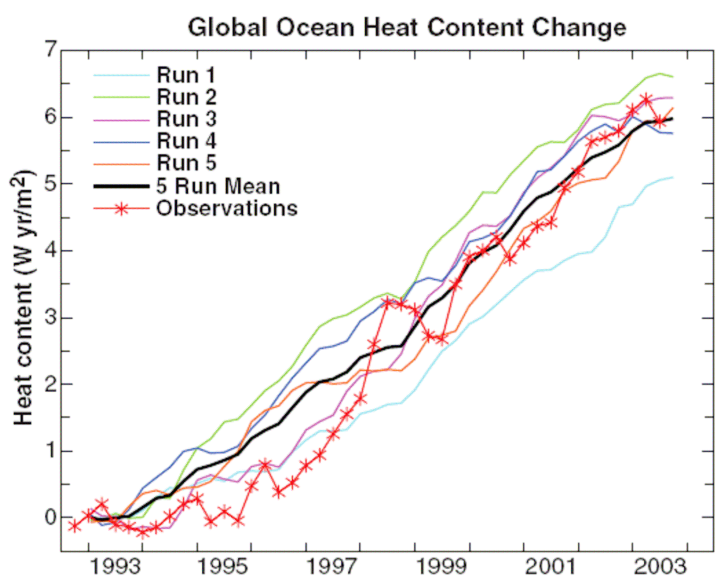

Figure 4-5: Global Ocean heat content predicted by five runs of the NASA-GISS AOGCM versus observations. Graph is taken from Hansen et al. (2005)[11] (see electronic book for full color version).

[11] Hanson, J. and coauthors, 2005: "Earth's Energy Imbalance: Confirmation and Implications", *Science*, 308, 1431-1435.

5 Conclusion

Based on the above discussion, the following main points are reached regarding the state of science of the global warming issue:

1. A broad base of measurements supports the fact that the earth's average temperature is warming, i.e. that warming is a global event. Warming trends are consistent between both hemispheres between surface measurements and those of the entire lower troposphere by satellites.

2. Attribution of the warming to increased greenhouse gas concentration is still uncertain. Values of climate forcing aside from that due to well-mixed greenhouse gases is still highly uncertain. In addition, Atmosphere-Ocean General Circulation Models (AOGCMs) are still problematic - many important feedback processes (most notably those associated with clouds) are parameterized, and they still produce better predictions when using artificial "flux-adjustments".

These persistent problems in AOGCMs are important because models only correctly match the warming over the last century a) when incorporating anthropogenic tropospheric aerosol forcing and b) when GHG warming is combined warming due to the water vapor feedback. However, the value of tropospheric aerosol forcing and the parameterization of water processes in AOGCMs are both areas of high uncertainty in climate modeling.

Because of this uncertainty, we do not have a high degree in confidence in future climate projections of AOGCMs, most notably those based on alternative GHG emission scenarios put forth by the IPCC.