ON CLIMATE SENSITIVITY

by Richard S. Lindzen, Ph.D.
with review assistance from Roy W. Spencer, Ph.D.

CO2 COALITION

Saving the people of the planet
from the people who are "saving the planet."

CO2 Coalition: Climate Issues in Depth Series

The CO2 Coalition of climate scientists and energy economists informs the public (1) about the net beneficial impact of carbon dioxide emissions on the atmosphere, land and oceans, and (2) the net negative impact on the economy, living standards and life expectancy of reducing these emissions by restricting access to energy.

CO2 COALITION
1621 North Kent Street, Suite 603
Arlington, Virginia 22209
www.co2coalition.org
info@co2coalition.org
571-970-3180

ON CLIMATE SENSITIVITY

by Richard S. Lindzen, Ph.D.
with review assistance from Roy W. Spencer, Ph.D.

CO2 COALITION

Saving the people of the planet
from the people who are "saving the planet."

CO2 Coalition: Climate Issues in Depth Series

Editor's Note

This is a superb paper to kick off the CO2 Coalition's Climate Issues in Depth Series. The topic lies at the heart of the public policy debate over climate and energy, and the author is one of America's most distinguished atmospheric physicists, MIT emeritus Alfred P. Sloan professor of meteorology Richard S. Lindzen.

Professor Lindzen has published over 200 scientific articles and books over a five-decade career. He has held professorships at the University of Chicago, Harvard University and MIT. He is a member of the National Academy of Science, the Norwegian Academy of Science and Letters, and the American Academy of Arts and Sciences. He is a fellow and award recipient of the American Meteorological Society and the American Geophysical Union. He is also a fellow of the American Association for the Advancement of Science, and was a lead author of the UN IPCC's third assessment report's scientific volume.

Since 1988, much of Professor Lindzen's research has highlighted the scientific uncertainties about the impact of carbon dioxide emissions on temperature. He has published frequently on the crucial and uncertain impact of clouds on temperature "feedbacks" – processes which cause substantial hypothesized magnification of CO2-based warming in the models used by the IPCC.

Providing review assistance to Professor Lindzen for this paper was another distinguished atmospheric climatologist, Dr. Roy W. Spencer. Dr. Spencer is one of the primary inventors of the remarkable scientific enterprise of "remote sensing" of temperature, humidity, and other properties crucial to climate by satellites. At his research professorship at the University of Alabama in Huntsville, he is both generator and guardian of satellite data relied upon by scientists and governmental bodies throughout the world.

Table of Contents

1. Introduction

It is commonly accepted that increasing CO_2 in the atmosphere should lead to some warming (e.g. Arrhenius, 1896; Callendar, 1938). This, *per se*, is not particularly worrisome. As has been recognized since antiquity, the dose makes the poison. The notion that any warming, however small, is evidence of coming disaster defies reason. Remember, in natural systems, fluctuations are the norm. For example, your body temperature always fluctuates a little. Skyscrapers always sway a little. This is a characteristic of all stable systems.

With respect to CO_2, the dose is determined by what we call climate sensitivity. By convention, this is the eventual total increase in global mean temperature associated with a doubling of CO_2. The reason we refer to a doubling is that the impact of each doubling is the same: *i.e.* a well-established equation based on empirical data shows that we get the same warming from an increase from 400 parts per million (ppm) to 800 ppm as we would from 200 ppm to 400 ppm (Pierrehumbert, 2011). That is to say, the impact of each added unit of CO_2 is less than the impact of its predecessor. In addition, reasonably straightforward calculations suggest that, all other indirect factors (*e.g.* clouds) being held constant, a doubling of CO_2 should produce about one degree Celsius (1°C) of direct warming—a value that is not generally held to be alarming (Wilson and Gea-Banacloche, 2012). The radiative forcing effect of CO_2 is measured in units of Watts per square meter. Each doubling of CO_2 is expected to provide about 3.7 Watts per square meter (Pierrehumbert, 2011). This can be compared to the natural flows of radiant energy in and out of the climate system, estimated to be 235 to 245 Watts per square meter (Trenberth *et al*., 2009).

Of course, CO_2 is not the only anthropogenic greenhouse gas, and according to the United Nations Intergovernmental Panel on Climate Change (IPCC, 2013) the increase in anthropogenic greenhouse forcing since the beginning of the industrial era (which happens to coincide with the end of the Little Ice Age) is already almost what one expects from a doubling of CO_2, and we have seen a welcome warming of about 1°C. After all, the Little Ice Age was hardly considered optimal. The IPCC does not claim all of this small warming is due to increased greenhouse gases, but even if it were, it does not, on the face of it, suggest a high sensitivity. However, most models employed by the UN's Intergovernmental Panel on Climate Change display higher sensitivities (currently ranging from 1.5° – 4.5°C). Moreover, the UN argues that higher values portend profound dangers (a dubious claim in its own right).

In order to explain what is going on, one has to go over the various aspects of the claims. This is, by no means, a simple task. It is, moreover, a task rendered more difficult because many attempts to present this issue to the public have been oversimplified to the point of being totally misleading to both those endorsing alarm and to so-called skeptics (a previously honorable designation, but now claimed to be equivalent to holocaust denial).

One of the most seriously misrepresented foundational issues is the Greenhouse (GH) Effect, itself. For starters, the phenomenon in the atmosphere differs importantly from the effect found in greenhouses. Therefore, Section 2 of this paper will be devoted to explaining the atmospheric Greenhouse Effect. Even this relatively correct depiction is essentially one-dimensional, and its application to the three-dimensional planet involves extremely questionable assumptions about, among other things, the dynamic transport (*i.e.* by motions of the atmosphere and the oceans) of heat both vertically and horizontally.

By now, the reader may well suspect that a full discussion will be tantamount to covering almost the totality of atmospheric and oceanic physics, and that this will be well beyond what is possible in a research review for even a knowledgeable lay audience. I will, however, try to cover enough to make evident the silliness of former Secretary of State John Kerry's peculiar claim that although physics and chemistry may be hard, climate is simple enough for a child to understand. (Warning: Some mathematics will be necessary.) Section 3, however, will continue to work with the one dimensional picture in order to illustrate some features of what are called feedbacks and how they determine climate sensitivity.

Exploration of explicit feedbacks will immediately require going to three dimensions, and this will be described in Section 4. Section 4 will examine dynamic heat transport and how it affects mean temperature. This will illustrate some profound difficulties with the simple picture of climate sensitivity.

Section 5 will discuss various approaches to determining climate sensitivity, and Section 6 will summarize the situation. The reader should be warned that this is a difficult subject, and that understanding it requires genuine effort.

2. The Atmospheric Greenhouse Effect

Let us assume for the moment that the earth has no atmosphere, and that the surface is non-reflecting. What would the temperature of the surface be? Incoming radiation would be about 341 Watts per square meter. In order for the earth to balance this, it would have to have a temperature given by the expression σT^4 where σ, the Planck constant, is $5.67\times10^{-8}\ \mathrm{W{\cdot}m^{-2}{\cdot}K^{-4}}$. Interestingly, this leads to a temperature of about 278.5 K or 5.5 C, at which temperature, the Planck function for the spectral distribution of radiation tells us that the radiation emitted by the earth is primarily in the infrared portion of the spectrum. This is only about 10 C less than today's 288 K. If we allow for a surface reflectivity of 0.1, then the incoming radiation is reduced to about 307 Watts per square meter, and we get a temperature of about 271 K or -2 C. This is still only 17 C less than today's mean temperature of 288 K.

The common claim that the earth would be 33 C less than today's temperature comes from including the reflectivity of clouds, which brings the reflectivity to about 0.3. This reduces the incoming radiation to 240 Watts per square meter and leads to a temperature of 255 K. We will ignore the implausibility of an atmosphere-free earth having clouds. Of course, even in this simple situation, the surface temperature will vary with latitude, but for convenience of presentation we will assume that the temperature represents some sort of average.

When the rest of our atmosphere is added, several things change because our atmosphere contains various substances (water vapor, CO_2, clouds and other less important gases) that absorb infrared radiation sufficiently to block radiation from the surface from being transmitted directly to space. This, in turn, leads to a sharp drop in temperature above the surface that destabilizes the air and leads to convection. Convection, in turn, limits the rate of decrease to something known as the dry adiabatic lapse rate, which is -9.8°C per kilometer for a dry atmosphere. The observed rate of decrease is closer to -6.5°C per kilometer, which is related to what is known as the moist adiabatic lapse rate. However, the greenhouse substances in the atmosphere diminish with altitude until, at some level, the infrared radiation can indeed escape to space. Due to the lapse rate, this level is colder than the surface, and the difference between this temperature and the surface temperature is what is referred to as the greenhouse effect.

Most discussions of the greenhouse effect restrict themselves to clear air where only the greenhouse gases are relevant. However, the infrared opacity of upper-level cirrus clouds is often large enough (Choi *et al*, 2005) that when such clouds are above the emission level for the greenhouse gases, they block the infrared radiation from the gases, and the new emission level is near the top of these clouds. This is very important because in the presence of such clouds, the presence of the greenhouse gases below these clouds becomes relatively irrelevant to the greenhouse effect. It should also be noted that when such clouds are absent, water vapor is far and away the most important greenhouse gas.

3. The Perturbed Greenhouse Effect and Feedbacks

Let us ignore the presence of upper-level cirrus clouds for the moment. When we add greenhouse gases to the atmosphere, we elevate the characteristic emission level and, because of convection that was described in Section 2, the new level is colder. As a result, infrared emissions to space are reduced and no longer balance the net incoming solar radiation. In order for balance to be restored, the troposphere must warm. This is illustrated in Figure 1.

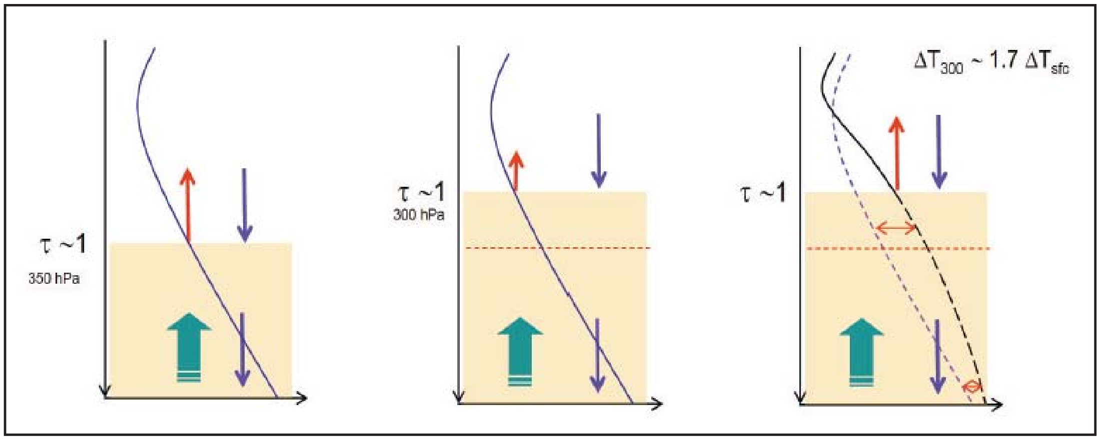


Figure 1. Temperature-height sections representing the global-average atmosphere, showing the temperature profile before adding more greenhouse gases (crudely represented by yellow shading, left panel); the radiative imbalance right after adding greenhouse gases causing the height of the infrared emission to space to rise to a higher, colder altitude where the loss of energy to space is less (center panel); leading to a warming of the temperature profile until radiative balance is once again restored (right panel).

It is this process that is associated with the claim that doubling CO_2 alone will lead to a warming of about 1°C. Note that at least in the tropics, convection leads to a moist adiabatic lapse rate. It turns out that such a lapse rate is not uniform with altitude. Rather, it requires that warming in the upper troposphere be greater than at the ground (Wallace and Hobbs, 2006). This has sometimes been erroneously claimed to be a signature of greenhouse warming. In point of fact, it should be characteristic of any warming regardless of cause and is due to the release of heat by the condensation of water vapor associated with moist convection.

The presence of upper-level cirrus modifies this picture as illustrated in Figure 2.

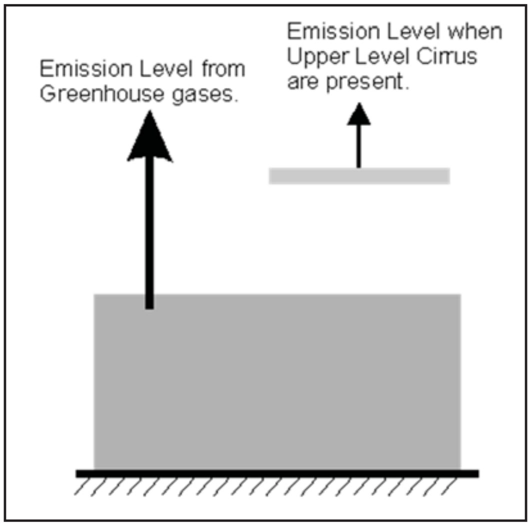


Figure 2. Cirrus clouds are at a higher altitude than the bulk of atmospheric greenhouse gases, leading to even weaker loss of infrared energy to outer space. As a result, cirrus clouds increase Earth's greenhouse effect.

Note that the characteristic emission level in the absence of clouds is around 6 km of altitude, while upper-level cirrus are often above 12 km. If upper-level cirrus coverage is constant in thickness and areal coverage, and occurs at the same temperature-altitude, then the only modification is to restrict the enhanced greenhouse effect to the region that is free of such clouds. However, such cloud cover is, in fact, highly variable and subject to change if the temperature changes. This brings us to the matter of feedbacks.

The most commonly discussed feedback is the so-called water vapor feedback (Manabe and Wetherald, 1975). In this early and highly influential paper, Manabe and Wetherald assumed (with little basis) that relative humidity would remain constant throughout the depth of the troposphere (where our weather occurs) when one increased CO_2. This implied that since saturation vapor pressure increases with temperature, specific humidity would increase with warming, and since water vapor is a powerful greenhouse gas, the impact of a doubling of CO_2 would be about double what it would be without such a feedback. Subsequent papers described this in terms of Bode's feedback analysis from electronics (Schlesinger, 1988; Hansen *et al.,* 1984; Roe and Baker, 2007) which is illustrated in Figure 3.

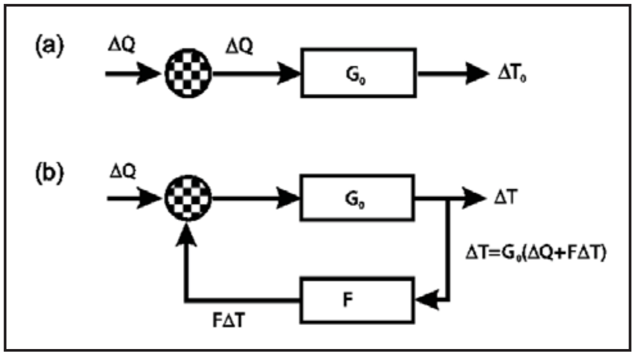


Figure 3. Schematic illustration of the climate system's departures from an assumed average state of energy equilibrium. An energy input (delta Q) causes changes through a system gain factor (G_0) resulting in a change in temperature (delta T), either without feedback (case a) or with feedback F (case b).

The resulting equation suggests a rather insidious aspect of feedbacks.

$$\text{Total Response } = \frac{\text{Unamplified Response}}{1-\sum \text{feedback factors}}$$

The feedback factor associated with the water vapor feedback is about 0.5. However, should there be any other positive feedback factors, the amplification rapidly increases to much higher values. In typical computer models of climate, such additional feedback factors associated with the effect of low level clouds on the reflection of visible light bring amplification factors to as high as 5. Note, however, that the contribution of these feedbacks to the sum of the feedback factors is still considerably less than the contribution of the alleged water vapor feedback. Of course, as even the IPCC acknowledges, all these feedbacks depend on the behavior of water in all its phases, and this behavior is very poorly represented in the models. In particular, models fail to describe the behavior of upper-level cirrus clouds. The very existence of such clouds and their substantial variability makes the description of the water vapor feedback incomplete unless one also considers the fact that this feedback only significantly operates in the variable area that is free of such clouds.

As it turns out, there are many things that can cause upper-level cirrus to vary. Only their dependence on temperature will determine their contribution to the feedback factors. In determining this dependence, the other sources of variability constitute noise. Despite this noise, a substantial number of independent analyses all conclude that the areal coverage of such clouds per unit cumulus convection decreases with temperature (Lindzen *et al*, 2001, Rondanelli and Lindzen, 2008, Horvath and Soden, 2008, Del Genio and Kovari, 2002). The last reference claimed to show cloud cover increasing with temperature, but actually showed that coverage per unit cumulus convection decreased pronouncedly. The radiative properties of such clouds appear to be primarily in the infrared (Choi *et al*, 2005). Thus, they should act as negative feedbacks.

Lindzen *et al.* (2001) referred to this as the *Iris Effect*, and found it to be sufficient to cancel other infrared feedbacks. Indeed, given that one can't really disentangle the water vapor feedback from the Iris Effect (given that the water vapor feedback is only effective over the area not covered by upper-level cirrus), it is probably more meaningful to simply refer to their combined effect as the infrared (or long-wave) feedback. That this combined long-wave feedback is essentially eliminated was confirmed by Trenberth and Fasullo (2009). The introduction of the Iris Effect into the model of the Max Planck Institute also essentially eliminated the long-wave feedback (Mauritsen and Stevens, 2015). Both these papers concluded that the only positive feedbacks had to be due to visible feedbacks from low level clouds. However, the contribution of such feedbacks to the total feedback system is generally less than 0.3, which will only bring the total response to less than about 1.5°C, assuming that the Iris Effect only cancels (rather than exceeds) any other long-wave feedbacks. This is at the bottom of the current IPCC model-based range of 1.5°C to 4.5°C warming for a doubling of atmospheric CO_2.

Interestingly, the latest IPCC assessment (IPCC, 2013) claims that there is no basis for preferring any particular value of sensitivity within their stated range of 1.5°C to 4.5°C. Quite frankly, this is simply a statement of ignorance, and can hardly be said to exclude values below or above the stated range. However, the fact that sensitive models need positive long-wave feedbacks strongly suggests that the values above 1.5°C are simply due to the incorrect treatment of upper-level cirrus.

4. The real climate system

In this section we will attempt to assess to what extent climate sensitivity is a useful metric for climate in general. Although the greenhouse effect, as described above, has been known to some extent or another since the 19th Century (Arrhenius, 1896), until the 1970s most treatments of major climate change did not particularly stress this process. Given the nature of past major climate variations, this may not be surprising. For example, a comparison of the present climate, that of the last glacial maximum (18 thousand years ago), and the Eocene (about 50 million years ago) shows that equatorial temperatures have not changed much, but that the temperature *difference* between the equator and the pole, ΔT_{e-p}, changed profoundly:

Present:	ΔT_{e-p} ~ 40°C
Last Glacial Maximum:	ΔT_{e-p} ~ 60°C (CLIMAP Project Members, 1976)
Eocene:	ΔT_{e-p} ~ 20°C (Shackleton and Boersma, 1981)

Obviously, the explanation of these past climates would consist in explanations of the relative stability of equatorial temperatures over time, and why the polar regions have varied so dramatically.

However, since greenhouse-induced global warming became the focus of climate concern, the emphasis shifted to the global mean temperature anomaly. An unexplained subsidiary mechanism (namely "polar amplification") was supposed to lead to the changes in ΔT_{e-p} automatically when mean temperature and globally averaged forcing change. As explained shortly, the meridional heat transport in the atmosphere and ocean is much more complicated than fluid flow in a pipe; nevertheless, this supposition sounds almost as though one were assuming that *mean* pressure rather than pressure *difference* along the pipe determines pipe flow, which is silly for the pipe as well as the climate system. The implausibility of the supposition is supported by the observation that among several models subjected to a doubling of CO_2, few actually exhibited a significant change in ΔT_{e-p} (Lee *et al*., 2008; Held and Suarez, 1978).

Moreover, the attempts to model the Eocene climate by simply cranking up greenhouse forcing generally led to meridional temperature distributions like today's, but with relatively uniform warming at all latitudes – including the equator (Huber and Sloan, 1999). Somewhat amusingly, Huber (2009) attempted to use the discovery of a giant snake fossil in Colombia to argue that Eocene equatorial temperatures were much warmer than shown by other proxies. As we will soon see, it is virtually impossible for today's ΔT_{e-p} to be the same as during the Eocene, thus eliminating the need for extraordinary special pleading concerning equatorial temperatures. More recently, Huber and Caballero (2011) have repeated the calculations with a model that does get DT_{e-p} more nearly correct. It is unclear what changes they made to the earlier model.

Meridional heat transport between the tropics and pole is due to something called baroclinic instability, which is a convective instability due to the existence of horizontal temperature gradients (Holton, 1972; Lindzen, 1990). In normal convection in non-rotating systems, the resulting temperature difference is determined by the nonlinear response to convective instability. For the rotating Earth, the geophysical situation is more complicated, with heat transport essentially along isentropic surfaces, which slope upward from the tropics to the high latitudes. The isentrope at the surface in the tropics essentially determines the polar tropopause temperature, and baroclinic equilibration determines the slope of this isentrope (Jansen and Ferrari, 2013). This slope appears to correspond to a $\Delta T_{e\text{-}p}$ at the tropopause level (about 6 km at the pole) of about 20°C which is the value of $\Delta T_{e\text{-}p}$ at the surface during the Eocene. It is also the value of $\Delta T_{e\text{-}p}$ in today's climate in the upper troposphere (Newell *et al.,* 1972).

This rather strongly suggests that baroclinic equilibration would lead to the Eocene climate were it not for other processes that are involved in determining $\Delta T_{e\text{-}p}$ at the surface. The existence of what is called the polar inversion seems a likely candidate. In the presence of ice, temperature at high latitudes increases rather than decreases with altitude. This inversion has long been observed, with an explanation offered by Wexler (1936). Relatively little has been done by way of explanation since then (Overland and Guest, 1991, Tsukernik, *et al*, 2004). The situation with respect to climate was crudely modelled by Lindzen and Farrell (1980). If this is the case, then there will be a contribution to global mean temperature that is separate from that due to greenhouse forcing. Figure 4 illustrates the situation.

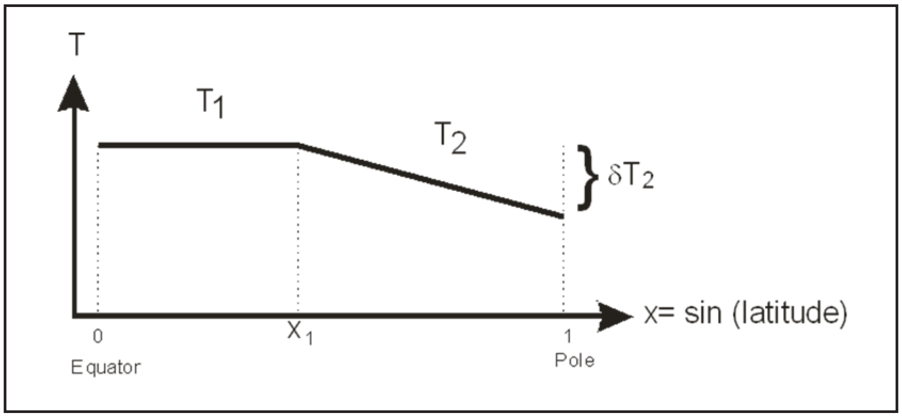


Figure 4. Schematic illustration of the decrease in temperature going from the tropics to the pole.

This rather simplistic analysis considers the separate contributions of greenhouse temperature changes (T_1) and dynamically produced changes to the equator-to-pole temperature difference (δT_2) to global mean temperature.

$$T = T_1 \text{ for } 0 \le x \le x_1$$

$$T = T_2 \text{ for } x_1 \le x \le 1$$

$$T_2 = T_1 - \delta T_2 \frac{x - x_1}{1 - x_1}$$

Here x_1 is the horizontal extent over which the Hadley circulation homogenizes temperature (Lindzen, 1990), while δT_2 is the equator-to-pole temperature difference.

$$\overline{T} = T_1 - \delta T_2 \frac{1 - x_1}{2}$$

$$\Delta \overline{T} = \Delta T_1 - \Delta(\delta T_2) \frac{1 - x_1}{2}$$

Note that ΔT_1 is the warming of the tropics, while $\Delta(\delta T_2)$ is the change in the equator-pole temperature difference. While ΔT_1 reflects greenhouse (*i.e.* radiative) forcing, $\Delta(\delta T_2)$ need not—especially when the latter is much greater than the former. All attempts to estimate climate sensitivity from paleo data (at least as far as I can tell) fail to distinguish between the two and attribute both contributions to greenhouse forcing in estimating climate sensitivity. This could be a major error.

$$\Delta\overline{T} = \Delta T_1 - \Delta(\delta T_2)\frac{1-x_1}{2}$$

From the above equation we see that in the absence of greenhouse forcing, ΔT_1 might be zero, while there might still be a contribution from $\Delta(\delta T_2)$, leading to the false conclusion that sensitivity was infinite. More realistically, if climate sensitivity to radiative forcing were very small, contributions from $\Delta(\delta T_2)$ could still lead one to falsely conclude that the sensitivity was large. The Milankovich theory (Milankovitch, 1941) of the glaciation cycles due to changes in Sun-Earth geometry provides an excellent example of this situation. Roe (2006) and Edvardsson *et al.* (2002) showed independently that there was excellent correlation between changes in summer insolation due to the Milankovitch cycles (the green line in Figure 5, below) and the best fit of orbital variations to the rate of change of the volume of Arctic ice (the black line).

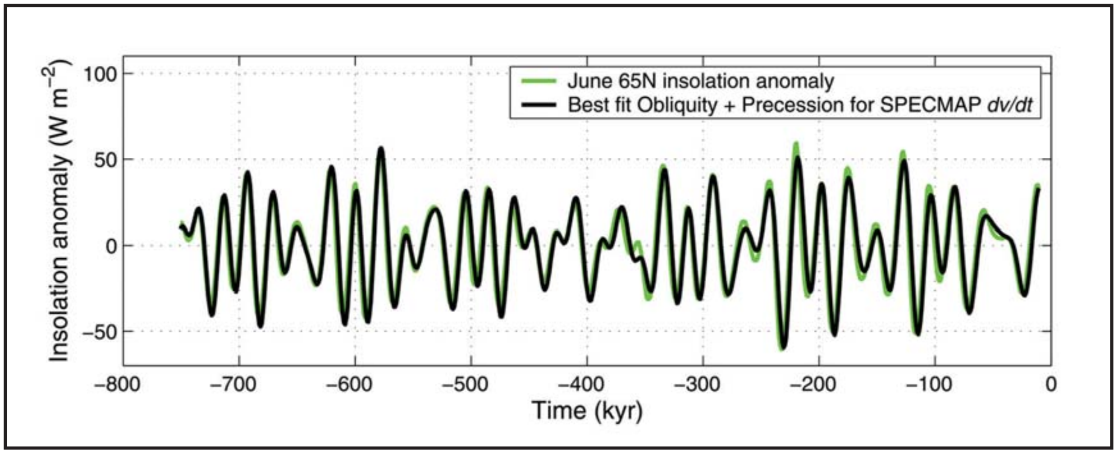


Figure 5. Milankovitch forcing and the rate of change of Arctic ice volume (from Roe 2006)

We see that insolation in the summer Arctic varies by about 100 Watts per square meter, a very large value compared to the global average of 240 Watts per square meter, and as Edvardsson *et al*. note, this is consistent with energy needed to freeze and melt the glaciers. As we have also seen, the temperature difference between the tropics and the pole during the glacial maxima was about 60°C, leading to about a 5°C change in global mean temperature (taking x_1=0.5). However, the annually and globally averaged insolation changed by only about 1 Watt per square meter. If we were to absurdly assume that it was this mean rather than the Milankovich parameter that forced the glaciation cycles, we could falsely conclude that the climate sensitivity was huge (Genthon *et al*., 1987).

5. Empirical determination of sensitivity

Section 4 showed why the use of paleoclimate data to determine climate sensitivity is likely to be inappropriate. However, the situation described in Section 4 might not be too important when dealing with the past century where changes in $\Delta T_{e\text{-}p}$ at the surface have been small (as, for that matter, have been changes in the mean temperature). Thus, a conventional greenhouse approach to evaluating sensitivity might still be approximately suitable for this very limited period. There have been several attempts at this, but they involve fairly complicated arguments that can only be sketched out in this relatively brief paper.

Before turning to systematic approaches, we may ask whether there is, in fact, any evidence that at least suggests unusual warming. As we see in Figure 6 , warming since 1978 is considerably less than almost all models used by the UN projected.

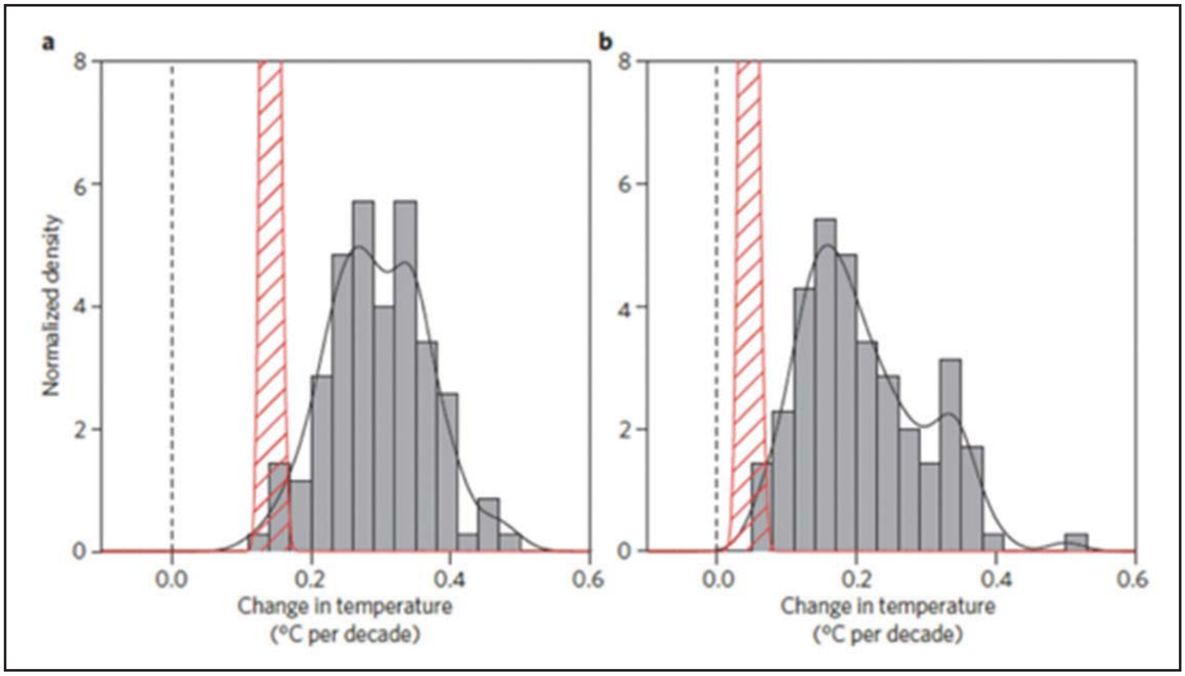
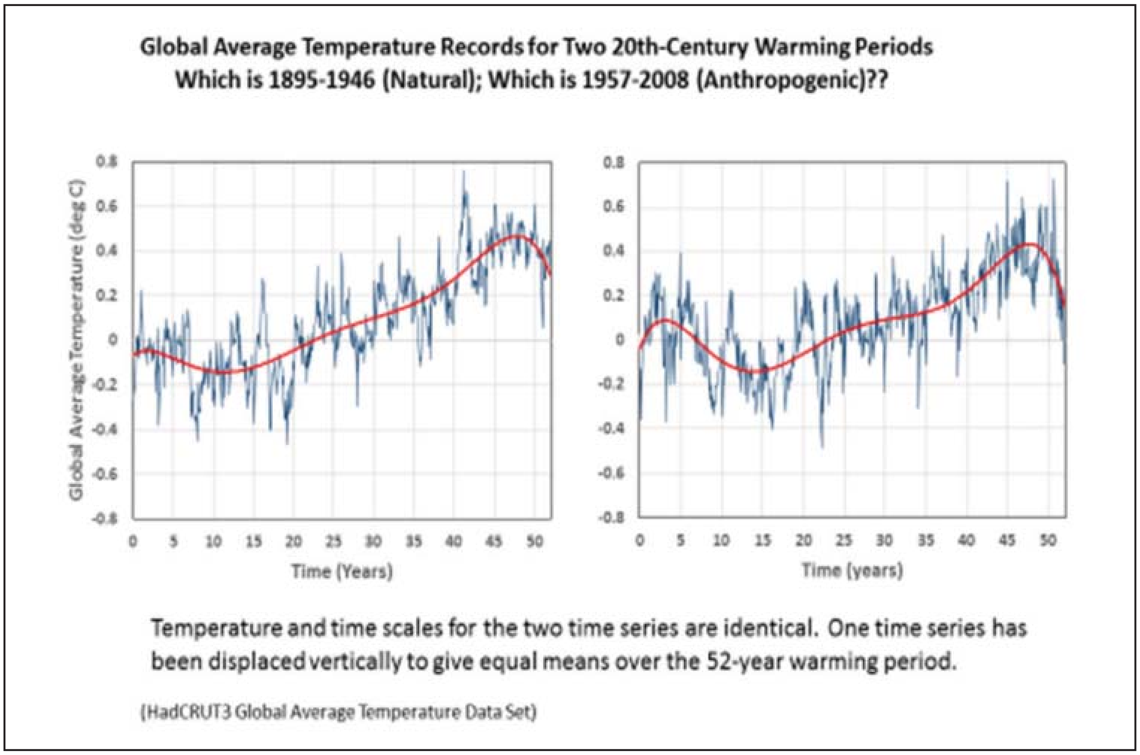


Figure 6. The frequency distribution of warming rates in climate models (gray bars) suggests the models are unrealistically warming about three times faster than observed in nature (red shading). Source: J.C. Fyfe *et al*., Overestimated Global Warming over the Past 20 Years, Nature Climate Change, 3 (2013), p. 767.

The UN acknowledges that anthropogenic contributions were only significant since the 1960s. Yet, as we see in Figure 7, warming from 1920 until 1940 was indistinguishable from the recent warming.



Global Average Temperature Records for Two 20th-Century Warming Periods
Which is 1895-1946 (Natural); Which is 1957-2008 (Anthropogenic)??

Temperature and time scales for the two time series are identical. One time series has been displaced vertically to give equal means over the 52-year warming period.

(HadCRUT3 Global Average Temperature Data Set)

Figure 7. Global temperature observations suggest that recent warming (left panel) looks nearly the same as warming before the 1940s, even though increasing CO_2 could not be responsible for the earlier period.

The contention of dangerous warming has always depended on special pleading rather than unusual behavior of the temperature record. Arguments about changes of tenths of a degree have been relatively pointless since the data are far from reliable for such small changes. Similarly, the use of demonstrably inadequate models to determine sensitivity is also inappropriate (as will be shown later in this section).

That said, the fact that there has been warming since the 19th Century has led to numerous attempts to use the temperature record to estimate sensitivity (Lewis and Crok, 2014; Lewis and Curry, 2014; Lewis and Curry, 2018). There have also been attempts to use satellite measurements of top of the atmosphere radiative fluxes in order to either estimate sensitivity in the context of a time-dependent one-dimensional model (Spencer and Braswell, 2014) or to evaluate feedbacks directly (Lindzen and Choi, 2009; 2011). All of these approaches have serious limitations, but when one excludes those with obvious errors, they all point to sensitivities at the bottom of IPCC estimates or less.

In order to better understand the approaches using the observed temperature history, it will be useful to examine the procedure in the context of a very simple model where climate sensitivity is specified, and where (very uncertain) aerosol reflectivity is used as an adjustment in order to bring these models into agreement with the observed temperature history. We begin with the IPCC's AR5 estimates of radiative total forcings (RF) of the modern climate system since 1750 (Figure 8).

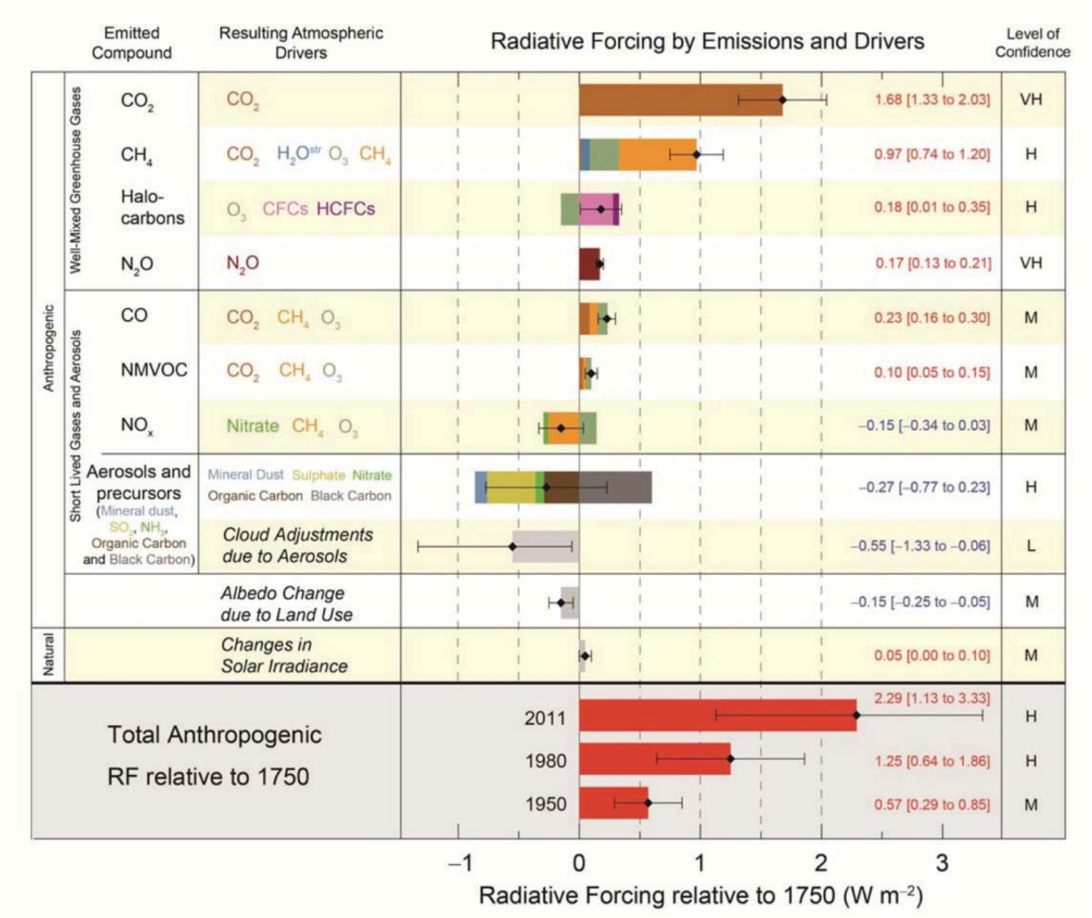


Figure 8. UN IPCC AR5 estimates of the various total radiative forcings of the global climate system since 1750 up until 2011. Note that the "aerosol" category has the largest uncertainties, and so is used as an *ad hoc* adjustment factor in the climate models to get better agreement with the history of observed global temperatures.

The extension of the line for 'Cloud adjustments due to aerosols' is not found in the IPCC report's Summary for Policy Makers (SPM) but is discussed in the text of the IPCC (2013) Working Group 1 report; it corresponds to what are referred to as indirect aerosol effects due to the potential impact of aerosols on cloud formation. The total anthropogenic RF includes aerosol compensation. We will separate this from GH forcing. Note that total GH forcing is about 80 percent of what would result from a doubling of CO_2. The IPCC offers ranges of uncertainty for all these quantities. We will, for the moment, simply stick with the central values and will return to the role of uncertainties later.

Finally, we will assume that the total anthropogenic greenhouse forcing follows the increase in CO_2 emissions in a smooth fashion. The resulting forcing as a function of time is shown in Figure 9.

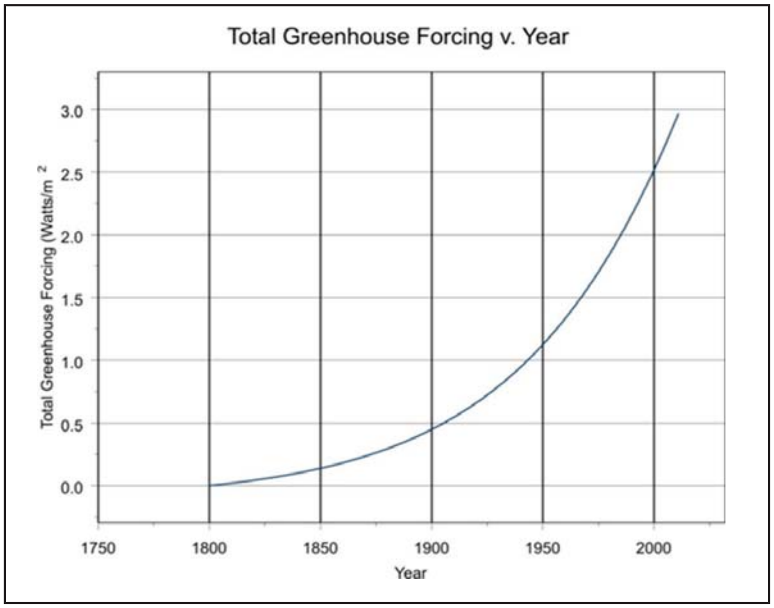


Figure 9. Simplified history of greenhouse forcing history since 1800, primarily from the increase in atmospheric CO_2.

The increase in this forcing is smoother than the actual forcing, but that will not be important for our conclusions.

While it is generally not emphasized, most models now also include forcing by volcanic eruptions. It turns out that many of these models use the estimate for volcanic forcing developed by Sato at the Goddard Institute for Space Studies (GISS: Sato *et al*., 1993; Sato *et al*., 2012). This is probably as good as any estimate, though there is substantial uncertainty. This forcing is illustrated in Figure 10.

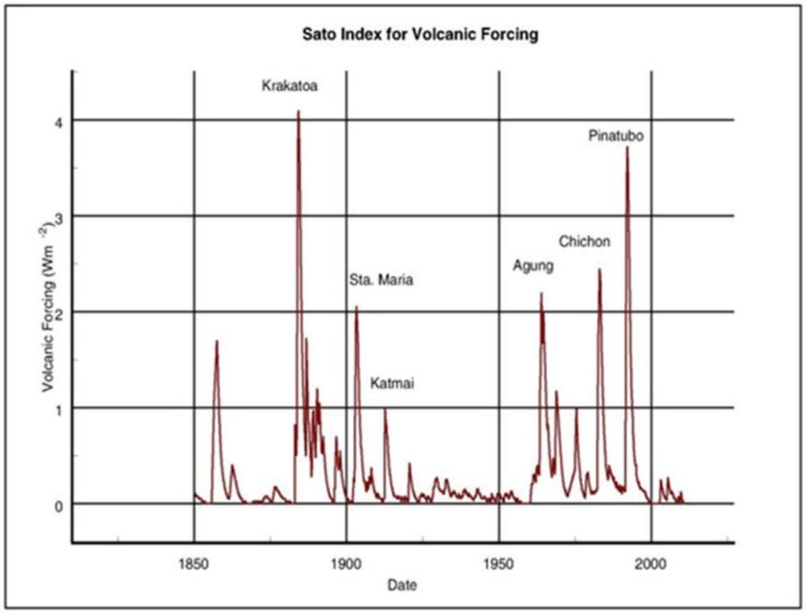


Figure 10. Volcanic radiative forcing events since 1850 (unlike Figs. 8 and 9, this forcing has a cooling effect).

Note that there are two clusters of volcanic activity separated by a period of relative quiet. One can use a very simple model to evaluate the impact of radiative forcing due to anthropogenic emissions and volcanoes. Such a model is illustrated in Figure 11 (Lindzen and Giannitsis, 1998), which we will use to further explore these issues.

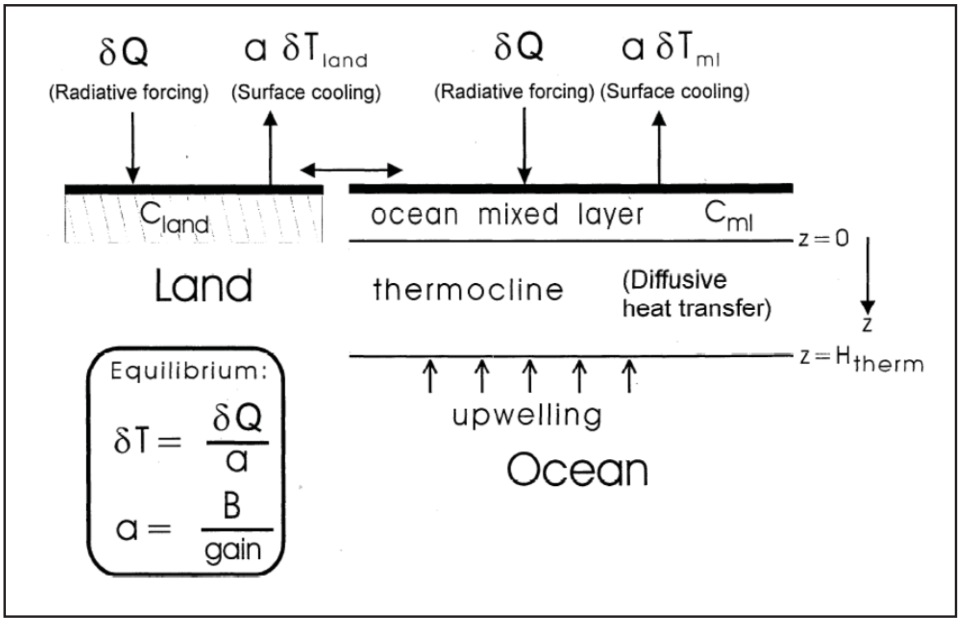


Figure 11. Geometry of a simple box model for the climate system response to radiative perturbations (Lindzen and Giannitsis, 1998).

The simple system in Fig. 11 is essentially what has been commonly used for IPCC scenario building. When the sensitivity is chosen to duplicate that of a coupled GCM (General Circulation Model), the results of the simple model and the GCM are very similar.

Note that in this simple model, the radiative forcing is taken to act at the surface (though not necessarily in the form of radiative transfer; radiative forcing is a flux whose nature changes from radiative at the top of the atmosphere to largely evaporative at the surface). The argument for this is that vertical air circulations in the troposphere fix the vertical temperature profile so that the energy flux at the surface must equal the radiative flux at the top of the atmosphere.

Finally, we must keep in mind that high sensitivity is associated with long response times for the temperature of the climate system. Radiative forcing is a flux of energy, and sensitivity is a ratio of temperature change to this flux. High sensitivity means that a small flux eventually produces a large temperature change, but, because the flux is small, the change will take a long time. The resulting response to the total anthropogenic greenhouse forcing is shown in Figure 12.

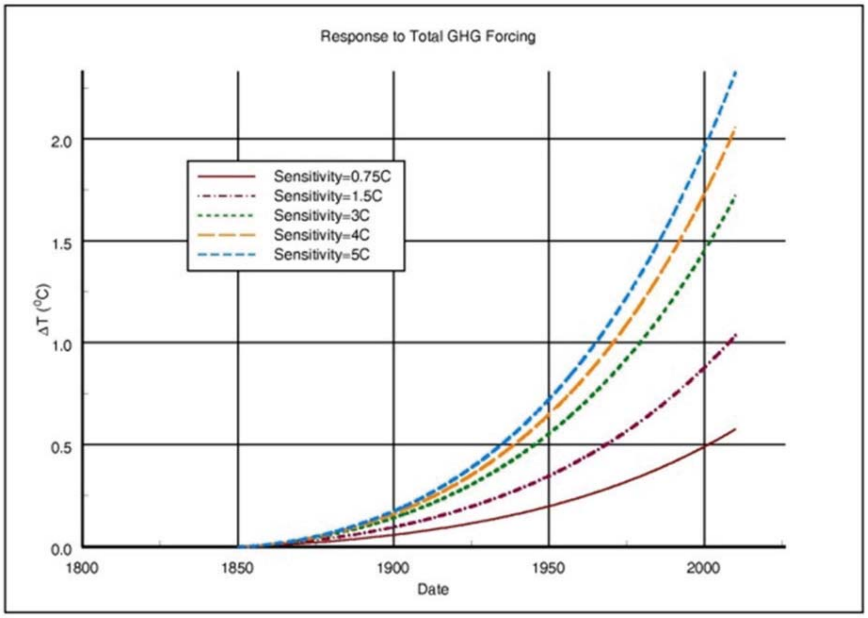


Figure 12. Temperature response to the greenhouse gas increase shown in Fig. 9 for a variety of climate sensitivities.

The response is not exactly proportional to the sensitivity because the higher sensitivities are associated with longer response times. The response at a particular intermediate time is referred to as the transient climate sensitivity (as opposed to the equilibrium climate sensitivity, which takes many years to be realized because of the ocean's large heat capacity).

We next evaluate the response to volcanic forcing, which forcing is by no means trivial. This response is shown in Figure 13.

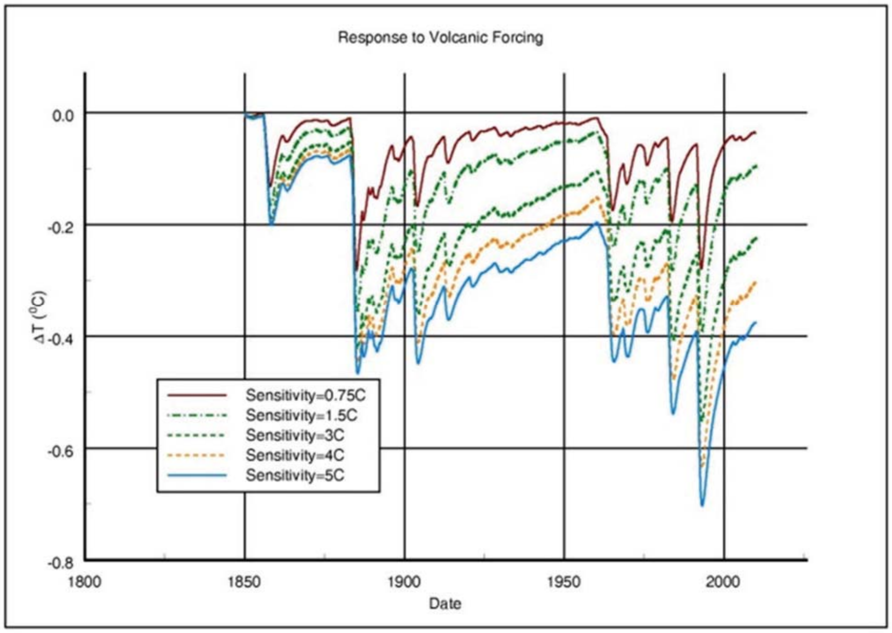


Figure 13. Temperature response to the volcanic forcing shown in Fig. 10 for a variety of climate sensitivities.

Note that knocking sensitivity down to 0.75°C gains about 0.3°C relative to models with sensitivity of about 3°C. Finally, in Figure 14 we show the response to both anthropogenic greenhouse gases and volcanoes.

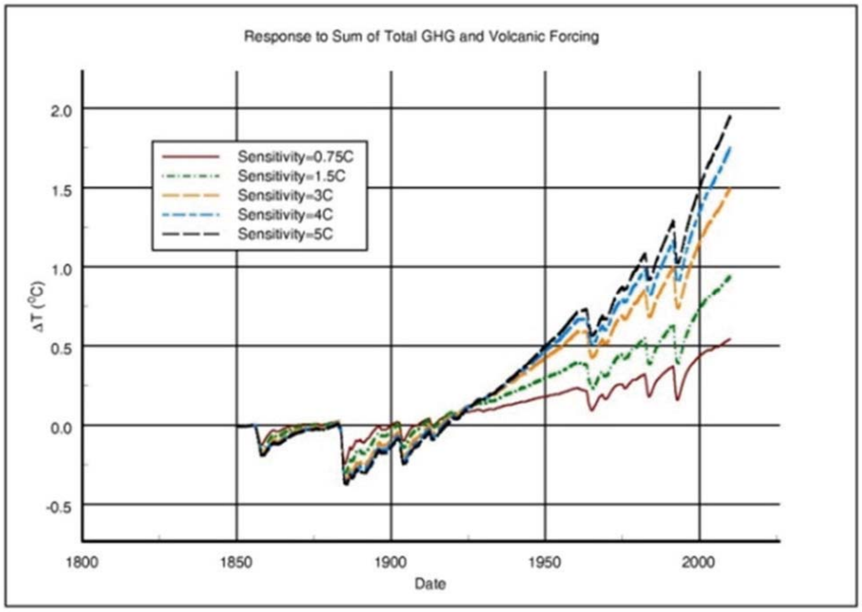


Figure 14. Temperature response to both greenhouse gas and volcanic forcing for a variety of climate sensitivities.

Interestingly, all the choices of sensitivity other than 0.75°C give more warming than is observed. However, the IPCC considers aerosol forcing to be part of anthropogenic forcing, and models choose the amount of aerosol forcing needed to bring their results into line with observed temperature changes (Kiehl, 2007). What results is shown in Figure 15.

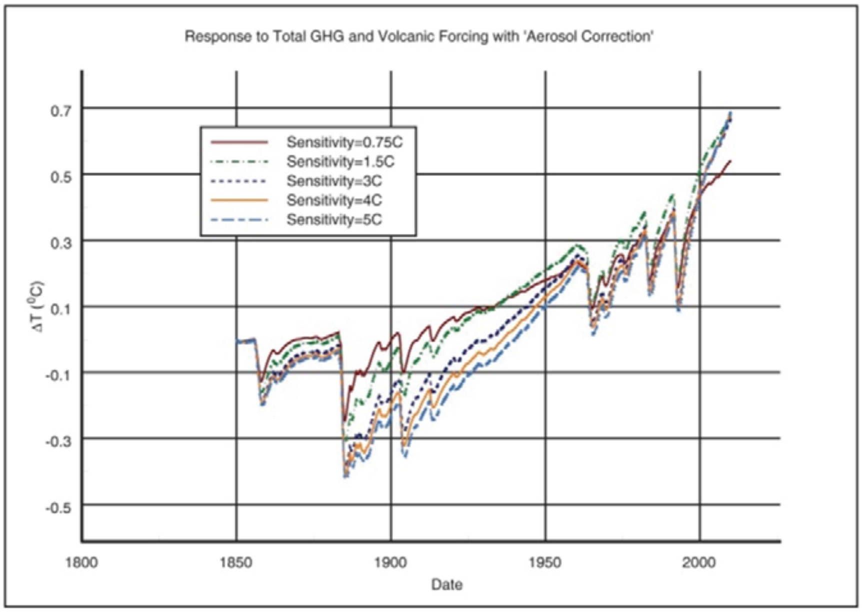


Figure 15. As in Fig. 14, but with a variety of uncertain anthropogenic aerosol forcings (Table 1) utilized to bring the model into better agreement with the observations.

Table 1 then shows the aerosol forcing that was needed to force agreement with observations.

Table 1. **Sensitivity in degrees C (for doubling of CO2)**	Fraction of GHG forcing cancelled by 'aerosols'
0.75	0
1.5	0. 25
3.0	0.481
4.0	0.525
5.0	0.543

Note that there is no need for highly uncertain 'aerosol' corrections with sensitivity on the order of 0.75°-1.0°C. However, for higher sensitivity, needed reductions begin to exceed IPCC estimates for aerosols. If recent work by Stevens (2015) is correct, aerosols are unlikely to provide more than 0.5 Watts m^{-2}, at which point sensitivities in excess of 1.5°C are impossible. If natural variability accounted for 49% of the recent warming (as the IPCC allows), then even 1°C is problematic.

Of course natural internal variability could become the new fudge factor, but then the attribution argument fails since the famous IPCC attribution of most of the recent warming to anthropogenic forcing depends on the claim that internal variability is not comparable to anthropogenic forcing. This peculiar claim was totally based on the desired model behavior rather than nature.

The problem of deducing climate sensitivity from data basically amounts to using the forcing in Fig. 9 and the total response for one of the curves in Fig. 15 to back out the sensitivity. Given the uncertainty in forcing, temperature data, aerosols, etc. would lead to a probabilistic distribution rather than a single answer. Moreover, any answer would depend on whether one assumed that all warming, not accounted for by volcanoes, was due to anthropogenic forcing or if one had some precise knowledge of natural variability due to such factors as ocean circulation systems or solar variability. A thorough review of such attempts is given by Lewis and Crok (2014). They concluded that such studies lead to an estimate for equilibrium sensitivity of about 1.75°C with a range of 1.25°C – 3°C.

As already mentioned, an alternate approach involves using global satellite radiative budget data available since 1985 in order to directly assess feedbacks. The idea here is quite simple. We simply look at how radiative fluxes at the top of the atmosphere vary in response to surface temperature fluctuations. If the change in flux is what one expects for the no-feedback case, then that would suggest the absence of feedbacks. If the outgoing flux is greater, then this would imply a negative feedback, and conversely, if the outgoing flux is less than this, then this would imply a positive feedback. Once the feedbacks are determined, one can determine the equilibrium climate sensitivity. Although this sounds straightforward, it is not. Among the problems are the following:

Problem 1. The satellite data from both the older ERBE and newer CERES satellite instruments are subject to limitations and adjustments that are uncertain.

Problem 2. The radiative imbalance is established over the short time scales associated with water vapor and clouds (order of days), but eventually, the system equilibrates and the radiative imbalance that one wishes to measure disappears. The equilibration time depends on the climate sensitivity, and is on the order of decades for positive feedbacks but as short as a year or less for negative feedbacks (Lindzen and Giannitsis, 1998). One must, therefore, confine oneself to time scales that are long compared to the feedback processes, but short compared to the equilibration times. If the time scales are too long, there will be a bias against negative feedbacks.

Problem 3. The factors that affect the top of the atmosphere (TOA) fluxes depend on factors other than surface temperature. These include water vapor, cloudiness, and such things as volcanoes. These non-feedback responses constitute noise when one is attempting to determine feedbacks. As Choi *et al.* (2014) show, the noise is not large enough to swamp long-wave feedbacks—especially in the tropics where the feedback processes are concentrated. However, for the short-wave fluxes, noise completely dominates the flux variations and essentially buries the feedback response. Due to the statistical way in which feedbacks are estimated from the data, noise can even cause positive feedback to be diagnosed when negative feedback exists (Spencer and Braswell, 2010).

In addition to discussing the use of the temperature record to estimate sensitivity, Lewis and Crok (2014) mention one study that does use satellite measured fluxes (Forster and Gregory, 2006), but as Lindzen and Choi (2011) show, this study uses too long a time scale for its regressions, and suffers from Problem 2 explained above. Nonetheless, the most likely sensitivity that Forster and Gregory suggest is 1.5°C which is at the bottom of the IPCC AR5 range.

The observations of top of the atmosphere radiative fluxes by Lindzen and Choi (2011), Spencer and Braswell (2010), and Trenberth and Fasullo (2009) show that there are no long-wave positive feedbacks and that the actual long-wave feedbacks may well be negative rather than positive. If there is a positive feedback due to water vapor, it is being countered by something like the Iris Effect described by Lindzen *et al.* (2001). Choi *et al*. (2014) and Spencer and Braswell (2010) showed that the short-wave feedbacks are swamped by noise and are indeterminate. Despite this, there are two points from Lindzen and Choi (2011) that are worth emphasizing. First, they compare model top of the atmosphere fluxes from the Atmospheric Model Intercomparison Project (AMIP) model runs (Gates *et al*., 1999) with observed variations of sea surface temperature. These vary greatly from the observed top of the atmosphere fluxes for the same sea surface temperatures—implying that whatever the real feedbacks are, they are not what the models are producing. The second point is that with the elimination of the long-wave feedback, one has eliminated the feedback that was used to imply a basis for global warming concern. One is now in the position of seeking a feedback anew to maintain global warming alarm, but without any clear conceptual basis for expecting such a feedback.

Mention should also be made of a novel approach to climate sensitivity by Shaviv (2008). Shaviv used solar cycle variations in ocean heat content to show that the solar cycle forcing was about 5-7 times greater than one would obtain from measurements of solar output. This is consistent with the suggestion that cosmic ray variations associated with the solar cycle induce changes in clouds. Comparison with solar cycle variations in surface temperature then leads immediately to estimates of climate sensitivity which is found to be less than 1°C.

6. Summary

The situation with respect to climate sensitivity is that we basically see no reason to expect high sensitivity. The original basis for considering that high sensitivity is possible (namely, the hypothetical water vapor feedback of Manabe and Wetherald, 1975) is clearly contradicted by the measurements of TOA radiative fluxes which show that the total long-wave feedback, including cirrus cloud variations, may even be negative. Analysis of the temperature data leads to the conclusion that if anthropogenic contributions are the cause of warming since the end of the Little Ice Age, and if aerosols are limited to a contribution of 1 Watt per square meter, then climate sensitivity in excess 1.5°C is precluded.

Have we then proven that dangerous warming is truly impossible? Not quite. Although current estimates of short-wave feedbacks don't even suggest positive feedback factors in excess of about 0.3 (with the possibility of negative values remaining), we can't preclude that something may someday be discovered that raises this to a value that is significantly larger. Our simple calculation that suggested that sensitivities in excess of 1.5°C were precluded depends upon the assumption that models are correct in producing negligible natural internal variability. It is, however, remotely conceivable that there was in reality (as opposed to in models) natural internal variability that was exactly what was needed to cancel the effect of high sensitivity, but that this internal variability would eventually be overwhelmed, and allow the high sensitivity to reveal itself.

This remote possibility is far from "settled science," and the thought that multi-trillion dollar policies would be implemented to putatively prevent this, seems far from rational. This is especially so when one considers that for about 95 percent of the time since complex life systems appeared (about 600 million years ago), levels of CO_2 were much higher than they are anticipated to become (as much as 10-20 times today's levels) without evidence of a relationship to global mean temperature.

References

Arrhenius, S. (1896), On the influence of carbonic acid in the air upon the temperature of the ground, *Philosophical Magazine and Journal of Science*, **5, 41**, 237-276.

Barron, E.J. (1987), Eocene equator-to-pole surface ocean temperatures: A significant climate problem? *Paleooceanography*, **2**, 729-739.

Callendar, G.S. (1938), The artificial production of Carbon Dioxide and its influence on temperature. *Proc. Roy. Met. Soc.,* doi:10.1002/qj.49706427503

Choi, Y.-S., C.-H. Ho, and C.-H. Sui (2005), Different optical properties of high cloud in GMS and MODIS observations, *Geophys. Res. Lett*., **32**, L23823, doi:10.1029/2005GL024616

Choi, Y.-S., H. Cho, C.-H. Ho, R.S. Lindzen, S.K. Park, and X. Yu (2014), Influence of non-feedback variations of radiation on the determination of climate feedback. *Theor Appl Climatol* doi:10.1007/s00704-013-0998-6

CLIMAP Project Members (1976), The Surface of the Ice-Age Earth, Science, 191, Issue 4232, pp. 1131-1137. DOI: 10.1126/science.191.4232.1131

Del Genio, A.D., and W. Kovari (2002), Climatic properties of tropical precipitating convection under varying environmental conditions. *J. Climate*, **15**, 2597-2615.

Edvardsson, R.S., K. G. Karlsson, and M. Engholmoe (2002), Accurate spin axes and solar system dynamics: Climatic variations for the Earth and Mars. *Astron. & Astrophys*., **384**, 689-701, doi:10.1051/0004-6361:20020029

Forster, P., and J. M. Gregory (2006), The climate sensitivity and its components diagnosed from Earth Radiation Budget data. *J. Climate*, **19**, 39-52.

Gates, W. L., and Coauthors (1999), An overview of the results of the Atmospheric Model Intercomparison Project (AMIP I). *Bull. Amer. Meteor. Soc.*, **80**, 29-55.

Genthon, G., J. M. Barnola, D. Raynaud, C. Lorius, J. Jouzel, N. I. Barkov, Y. S. Korotkevich & V. M. Kotlyakov (1987), Vostok ice core: climatic response to CO_2 and orbital forcing changes over the last climatic cycle. *Nature*, **329**, 414–418.

Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy, and J. Lerner (1984), Climate sensitivity: Analysis of feedback mechanisms. In *Climate Processes and Climate Sensitivity*. J.E. Hansen and T. Takahashi, Eds., AGU Geophysical Monograph 29, Maurice Ewing Vol. 5. American Geophysical Union, pp. 130-163.

Held, I.M., and M. Suarez (1978), A two-level primitive equation atmospheric model designed for climatic sensitivity experiments. *J. Atmos. Sci.*, **35**, 206-229.

Holton, J.R. (1972), *An Introduction to Dynamic Meteorology*, Academic Press, 319 pp.

Horvath, A. and B.J. Soden (2008), Lagrangian Diagnostics of Tropical Deep Convection and Its Effect upon Upper-Tropospheric Humidity, *Journal of Climate*, DOI: 10.1175/2007JCLI1786.1

Huber, M. (2009), Climate change: Snakes tell a torrid tale, *Nature*, **457**, pp. 669-671, doi:10.1038/457669a

Huber, M. and R. Caballero (2011), The early Eocene equable climate problem revisited. *Clim. Past*, **7**, 603–633, doi:10.5194/cp-7-603-2011

Huber, M. and L. C. Sloan (1999), Warm climate transitions: A general circulation modeling study of the Late Paleocene thermal maximum (about 56 Ma), *J. Geophys. Res.-Atmos.*, **104**, 16633–16655. doi:10.1029/1999JD900272.

IPCC, 2013: Climate Change 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Jansen, M., and R. Ferarri (2013), Equilibration of an atmosphere by adiabatic eddy fluxes. *J. Atmos. Sci.*, ***70***, doi: 10.1175/JAS-D-13-013.1

Kiehl, J. T. (2007), Twentieth century climate model response and climate sensitivity. *Geophys. Res. Lett.*, **34**, L22710, doi:10.1029/2007GL031383.

Lee, M.I., M.J. Suarez, I.S. Kang, I.M. Held, and D. Kim (2008), A moist benchmark calculation for the atmospheric general circulation models, *J. Clim.*, **21**, 4934-4954 doi: 10.1175/2008JCLI1891.1

Lewis, N., and M. Crok (2014), *A Sensitive Matter: Has the IPCC Buried Evidence Showing Good News About Global Warming?* The Global Warming Policy Foundation, 65pp.

Lewis, N. and J.A. Curry (2014), The implications for climate sensitivity of AR5 forcing and heat uptake estimates. *Climate Dynamics*, doi:10.1007/s003820142342y.

Lewis, N. and J.A. Curry (2018), The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity. *J. Climate*, **31**, 6051-6071.

Lindzen, R.S. (1990,93), *Dynamics in Atmospheric Physics*, Cambridge Univ. Press, 310 pp.

Lindzen, R.S. and Y.-S. Choi (2009), On the determination of climate feedbacks from ERBE data, *Geophys. Res. Ltrs.*, **36**, L16705, doi:10.1029/2009GL039628.

Lindzen, R.S. and Y.-S. Choi (2011), On the observational determination of climate sensitivity and its implications. *Asian Pacific J. of Atmospheric Science,* **47**, 377-390, doi:10.1007/s13143-011-0023-x

Lindzen, R.S., M.-D. Chou, and A.Y. Hou (2001), Does the Earth have an adaptive infrared iris? *Bull. Amer. Met. Soc.* **82**, 417-432.

Lindzen, R.S. and B. Farrell (1980), The role of polar regions in global climate, and the parameterization of global heat transport. *Mon. Wea. Rev.*, **108**, 2064-2079.

Lindzen, R.S., M.-D. Chou, and A.Y. Hou (2001), Does the Earth have an adaptive infrared iris? *Bull. Amer. Met. Soc.* **82**, 417-432.

Lindzen, R.S., and C. Giannitsis (1998), On the climatic implications of volcanic cooling. *J. Geophys. Res.-Atmos.*, **103**, D6, 5929-5941.

Manabe, S. and R.T. Wetherald (1975), The effects of doubling the CO_2 concentration on the climate of a general circulation model. *J. Atmos. Sci*., **32**, 3-15.

Mauritsen, T. and B. Stevens (2015), Missing iris effect as a possible cause of muted hydrological change and high climate sensitivity in models, *Nature Geoscience*, doi: 10:1038/NGEO2414.

Milankovitch, M. (1941), Kanon der Erdbestrahlung und seine Andwendung auf das Eiszeiten-problem, *R. Serbian Acad*., Belgrade

Overland, J.E., and P.S. Guest (1991), The Arctic snow and air-temperature budget over sea ice during winter. *J. Geophysical Research-Oceans*, **96**, 4651–4662

Newell, R.E., J. W. Kidson, D. G. Vincent, and G. J. Boer (1972), *The Circulation of the Tropical Atmosphere and Interactions with Extratropical Latitudes, Vol. 1*. Cambridge, MA: M.I.T. Press, 258 pp.

Pierrehumbert, R.T. (2011), *Principles of Planetary Climate*, Cambridge University Press, 674pp.

Roe, G. (2006), In defense of Milankovitch. *Geophys. Res. Lett*., **33**, doi:10.1029/2006GL027817

Roe, G. and M. Baker (2007), Why Is climate sensitivity so unpredictable? *Science,* **318**, 629-632 doi: 10.1126/science.1144735s, 154 pp.

Rondanelli, R.F. and R.S. Lindzen (2008), Observed variations in convective precipitation fraction and stratiform area with SST. *J. Geophys. Res.,* **113**, D16119, doi:10.1029/2008JD010064.

Sato M., J.E. Hansen, M.P. McCormick, and J.B. Pollack (1993), Stratospheric aerosol optical depths, 1850–1990. *J. Geophys. Res*. **98,** 22987–22994.

Sato M., J.E. Hansen, A. Lacis, M.P. McCormick, J.B. Pollack, L. Thomason, and A. Bourassa (2012), *Stratospheric aerosol optical thickness in the GISS climate model.* http://data.giss.nasa.gov/modelforce/strataer/

Schlesinger M.E. (1988), Quantitative Analysis of Feedbacks in Climate Model Simulations of CO_2-Induced Warming. In: Schlesinger M.E. (eds) *Physically-Based Modelling and Simulation of Climate and Climatic Change.* NATO ASI Series (Series C: Mathematical and Physical Sciences), **243**. Springer, Dordrecht.

Shackleton, N., and A. Boersma (1981), The climate of the Eocene ocean, *J. Geol. Soc. London*, **138**, 153-157.

Shaviv, N.J. (2008), Using the oceans as a calorimeter to quantify the solar radiative forcing, *J. Geophys. Res*., **113**, A11101, doi:10.1029/2007JA012989.

Spencer, R. W., and W. D. Braswell (2010), On the diagnosis of radiative feedback in the presence of unknown radiative forcing. *J. Geophys. Res*., **115**, D16109, doi:10.1029/2009JD013371.

Spencer, R. W., and W. D. Braswell (2014), The role of ENSO in global ocean temperature changes during 1955-2011 simulated with a 1D climate model. *Asia-Pacific J. Atmos. Sci.*, **50(2),** 229-237.

Stevens, B. (2015), Rethinking the lower bound on aerosol radiative forcing. *J. Climate*, **28**, 4794-4819. doi:10.1175/JCLI-D-14-00656.1

Trenberth, K. E. and J.T. Fasullo (2009), Global warming due to increasing absorbed solar radiation. *Geophys. Res. Lett*., **36**, L07706.

Trenberth, K. E., J.T. Fasullo, and J. Kiehl (2009), Earth's global energy budget. *Bull. Amer. Meteor. Soc*., March, 311-323.

Tsukernik, M., T. Chase, M. Serreze, R. Barry, R. Pielke, B. Herman, and X. Zeng, (2004), On the regulation of minimum mid-tropospheric temperatures in the Arctic. *Geophysical Reseach Letters*, **31**, doi:10.1029/2003GL018831.

Wallace, J., and P. Hobbs (2006), *Atmospheric Science: An Introductory Survey (2nd Ed.),* Academic Press, 504pp.

Wexler, H. (1936), Cooling in the lower atmosphere and the structure of polar continental air. *Mon. Wea. Rev.*, **64**, 122-136.

Wilson, D.J. and J. Gea-Banacloche, Simple model to estimate the contribution of atmospheric CO2 to the Earth's greenhouse effect, *American Journal of Physics*, **80** 306 (2012) p. 314.

CO2 Coalition Board of Directors

Jan Breslow, MD: Fredrick Henry Leonhardt Professor, Rockefeller University; Head, Laboratory of Biochemical Genetics and Metabolism; Senior Physician, Rockefeller Hospital.

Bruce Everett, PhD: Adjunct Professor of International Business at the Georgetown School of Foreign Service; Adjunct Associate Professor of International Business at the Fletcher School, Tufts University.

Gordon Fulks, PhD: University of Chicago Laboratory for Astrophysics; Mission Research Corporation, Corbett, Oregon.

Will Happer, PhD: Cyrus Fogg Brackett Professor of Physics (emeritus), Princeton University; former Director of Research, U.S. Department of Energy, and Senior Director of Emerging Technologies, National Security Council.

Patrick Moore, PhD: Co-founder and 15-year leader of Greenpeace (1971-1986); Chairman and Chief Scientist, Ecosense Environmental; Leader, Campaign to Allow Golden Rice Now.

Norman Rogers: Founder of Rabbit Semiconductor company; policy advisor to The Heartland Institute; member of the American Geophysical Union and the American Meteorological Society.

Jeffrey Salmon, PhD: former Senior Policy Advisor to the Secretary, Chief of Staff in the Office of Science, Associate Under Secretary for Science, and Director of Resource Management in the Office of Science, U.S. Department of Energy.

Leighton Steward: geologist, author, member of the Right Climate Stuff (Ex-NASA Climate Research Team).

Executive Director

Caleb Rossiter, PhD: climate statistician, former professor, American University School of International Service and Department of Mathematics and Statistics.

December 2019

CO2 COALITION