Central Coast Climate Science Education

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Lesson 8: Climate Sensitivity

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In this Lesson we take up the following question: Given some process which acts to disturb the energy balance of the climate system by adding energy to it, by how much will the global surface temperature increase? The process that we are most concerned with is of course the radiative forcing resulting from the trapping of outgoing infrared radiation due to the increased level of CO_2, which in turn is due to the burning of fossil fuels. Since it is impossible to project with any certainty what course of action will be taken, if any, to curb this increase, climate scientists have defined a number of possible 'scenarios' for future greenhouse gas emission rates for the next several decades. For any one of these scenarios the forcing from the continued emission of greenhouse gases can be calculated. (Unhappily, the ***actual*** trajectory of greenhouse emissions since these scenarios were defined has been as bad, or slightly worse, than the most pessimistic of these scenarios.) If one considers any of these scenarios, the questions we consider in this Lesson are: How much will the global surface temperature increase and how rapidly will it increase?

The concept of ***climate sensitivity*** is a key one in addressing these questions. In a nutshell, climate sensitivity is usually defined to be the temperature rise resulting from a doubling of the carbon dioxide concentration in the atmosphere. The point of this concept is that it incorporates all the feedbacks that are brought into play as a result of subjecting the climate system to some 'forcing'.

As discussed in **Lesson 2 "Forcings" and "Feedbacks"** there are other 'forcings' besides carbon dioxide, so the concept of climate sensitivity can be generalized to include the temperature rise resulting from the 'forcing' from other sources (for example, changes in the sun's brightness) with a 'forcing' equivalent to a doubling of the carbon dioxide.

Does climate sensitivity depend upon the particular forcing involved? For example, would the effects of an increase in the Sun's brightness equivalent to the forcing resulting from doubling the amount of carbon dioxide have the same effects as the doubling of carbon dioxide itself has? In a very rough sense this seems to be the case, but there are important differences.

A good example of such a difference is the change in temperature of the stratosphere, (the layer of the atmosphere above the troposphere) resulting from these two kinds of forcings. In the troposphere, (the portion of the atmosphere ranging from the surface up to 30,000 to 55,000 feet in height, depending upon latitude), the temperature drops steadily with altitude, but in the stratosphere it begins to increase with height due to the absorption of ultraviolet solar radiation by the ozone layer. Both types of forcing would be expected to warm the troposphere, but forcing due to an increase in ***solar radiation*** will ***increase*** the heating via absorption of ultraviolet radiation, and thus ***warm*** the stratosphere. However an increase in the forcing due an increase of carbon dioxide will result in stratospheric ***cooling*** as less of the infrared energy emitted upwards by the Earth reaches the stratosphere because it is absorbed by the extra carbon dioxide. Observations strongly indicate that the stratosphere ***has cooled*** while the troposphere ***has warmed*** over the last few decades. This is further evidence that greenhouse gases, not the sun, have been responsible for the warming of the last few decades.

The concept of climate sensitivity is not meaningful unless one also specifies how quickly and for how long the forcing is applied, and importantly, how long afterward one waits to see by how much the temperature eventually rises. After all, if we were somehow to magically double the amount of carbon dioxide in the atmosphere instantaneously, surely we would not feel the full effects of the increased heat trapping within the next 2 minutes!

Climate scientists define the ***equilibrium*** **climate sensitivity** as the final resulting temperature increase if the forcing agent is increased (e.g. by increasing the CO_2 concentration) and then is maintained at that value indefinitely. Often the equilibrium climate sensitivity is specified in terms of the temperature increase resulting from a doubling of the CO_2 concentration in the atmosphere, since detailed radiative transfer calculations show that over a range in CO_2 concentrations relevant to the next century or two, the forcing increases by about the same amount for ***every doubling*** of the CO_2 concentration: specifically, by about 3.7 watts per square meter. (The mathematically inclined will recognize this means that the change in forcing is proportional to the ***logarithm*** of the concentration of CO_2 relative to its preindustrial value.)

Figure 1 (below), generated by a climate simulation model, shows one estimate of how long it takes for energy balance to be reestablished--that is, how long it takes for the new equilibrium to be established following a rapid increase in forcing. (Of course there is no moment when equilibrium is exactly established, since internal natural variability will continually produce small excursions above and below this new equilibrium value.) The various heat capacities of components of the climate system and the time for stirring up the various layers of the ocean are the key factors. Notice in this Figure, that after 100 years the time axis is 'stretched out' and plotted on a logarithmic scale.

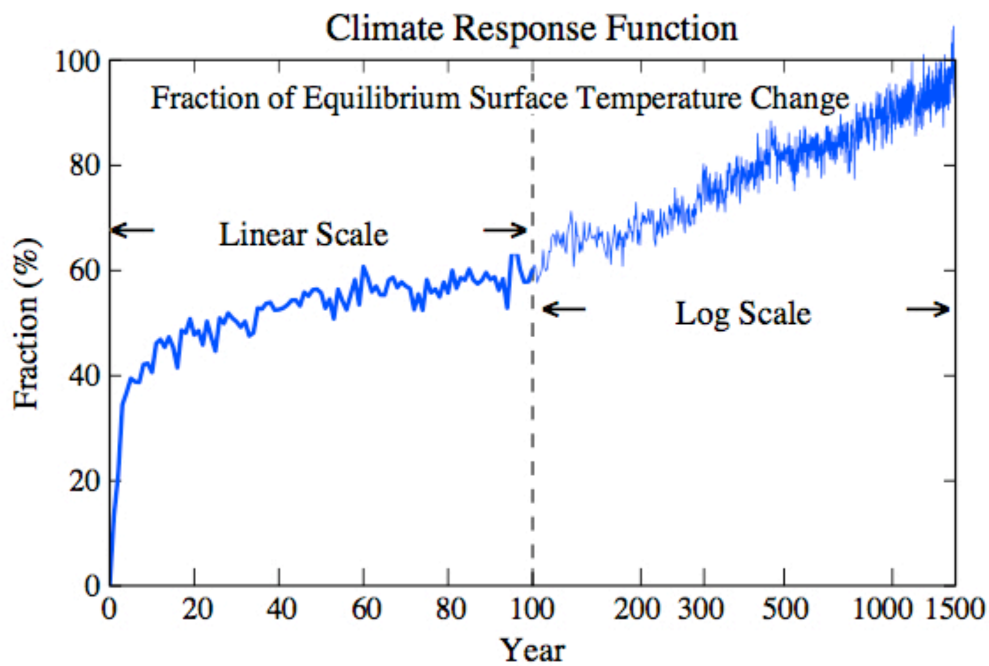

Figure 1.
The approach to the final change in surface temperature after a 'forcing' is introduced. Note that even after 100 years the temperature has warmed to only 60% of its final equilibrium value.

As discussed below, the best current estimates for the equilibrium climate sensitivity are around 3 to 4 ^{o}C. So, for example, imagine starting with the climate system being very nearly in energy balance prior to the industrial revolution as it has been for several thousand years with the CO_2 concentration in the atmosphere at about 280 ppm. Then, suppose rather suddenly the CO_2 concentration were to be doubled to a value of 560 ppm. As you can see from Figure 1, the result would be that an initial sharp rise in temperature would occur in just a few years to about 40% of its new equilibrium value—0.4 * 3.5 ^{o}C = 1.4 ^{o}C. for an equilibrium climate sensitivity of 3.5 ^{o}C. But then ocean circulation would distribute this heat to deeper depths and the very large heat capacity of the ocean ("thermal inertia") would slow the increase in temperature. Not until about 1500 years had elapsed would the temperature have risen to where the increased outgoing infrared radiation of the warmer Earth restored energy balance, but at a level 3-4 ^{o}C higher than it started with at the beginning of the industrial revolution. It is this "thermal inertia" coupled with the long life of injected CO_2 that leads climate scientists to tell us that we are already "locked in" to further warming.

(Here is an everyday example of thermal inertia and a new equilibrium temperature: My garage workshop has a thick concrete floor and heavy walls partly surrounded by dirt. It's large heat capacity and pretty good insulation means it stays at a pretty constant temperature year around—about 55 to 60 ^{o}F. In the summer the outside temperature during the day is much hotter. If I open the garage door and let that warm air in (a forcing) the garage will not heat up very much as long as I don't leave the door open for very long. But if I continue the forcing by leaving the door open all day long, the garage walls and floor will begin to approach a new equilibrium temperature well above its previous value.)

Of course such an instantaneous doubling does not really occur, so climate scientists have also introduced the concept of ***transient*** **climate sensitivity.** Transient climate sensitivity is the temperature response as the forcing is gradually and continuously increased. (There is a precise definition of the transient sensitivity, but we do not need to go into that level of detail.)

Because some of the feedbacks in the climate system are slow to respond and especially because of the large thermal inertia due to the huge heat capacity of the ocean, the ongoing, or transient, temperature increase at a given level of the increasing CO_2 is significantly less than the equilibrium response will be--typically about 50-65%. Figure 2 shows the transient and equilibrium temperature responses as a function of the concentration of CO_2 in the atmosphere from a climate model computer simulation.

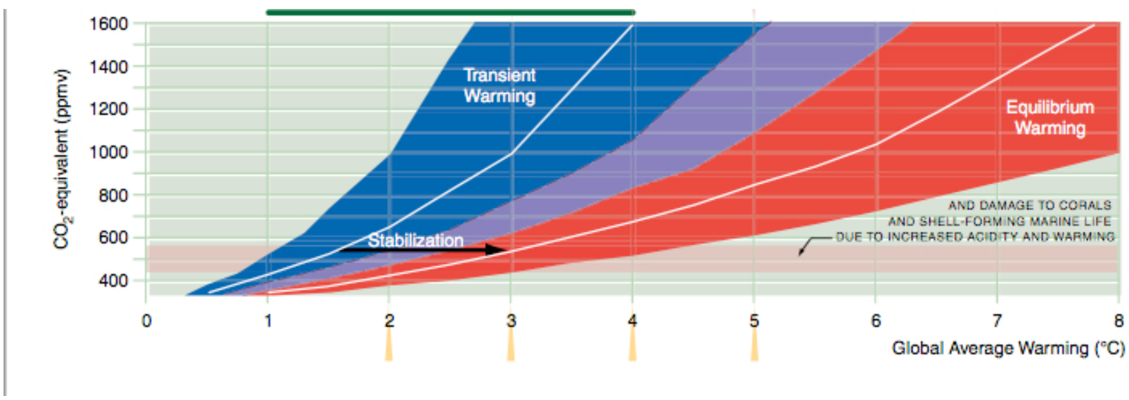

Figure 2.

The blue area shows the range of estimated ***transient*** temperature responses to various levels of CO_2 concentrations, while the red area shows similar estimates for ***equilibrium*** temperature responses. The two white lines are the best estimates for these two ranges of estimates.

The current CO_2 concentration is nearly 400 ppm and is rising at about 2 ppm each year. Compared to the Earth's average surface temperature prior to the rapid CO_2 increase marking the industrial revolution, there has been an increase of about 0.8 ^oC. (Reading the temperature value on the horizontal axis scale when the white line marked "transient warming" reaches the level of CO_2 on the vertical axis scale at 400 gives about this value of 0.8 ^oC.

Assuming the CO_2 level is continually increased, when the CO_2 level has increased to 800, the best estimate for the transient, continually rising temperature—what we would actually experience at the time—is given by following the white line in the blue portion of the figure to where it crosses the 800 level on the vertical scale, and reading the temperature increase on the horizontal scale at that point. This is about 2.4 ^oC, or an increase of about 1.6 ^oC from today's starting point of 0.8 ^oC. If the CO_2 level is then ***stabilized*** at 800--i.e. when it has doubled from 400--the warming will ***continue*** until a new equilibrium is reached after many centuries. This increase in temperature at this new equilibrium is found by moving to the right on the graph at the 800 level, until we come to the white line in the red part of the graph. The value of the temperature increase where the equilibrium white line is intersected by moving to the right at the 800 level is about 4.6 ^oC or an increase of about 3.8 ^oC, i.e. the simulated equilibrium climate sensitivity in this case about 3.8 ^oC.

We have gone through this in some detail for the following two reasons:

1) Surveys reveal that among professional climate scientists, about 97% are of the opinion that human activities have caused, and will continue to cause, a significant warming of the Earth's climate and that the associated impacts of continuing this activity are almost certain to have very serious consequences. These consequences are the topic of Lesson 9. Of the remaining 3% of professional climate scientists, nearly all of them will agree that human activity is responsible for the rapid increase in CO_2 during the recent past and that this increase in CO_2 (and the other greenhouse gases) will cause the temperature to rise. After all, the greenhouse effect is well understood physics and moreover is confirmed by direct satellite measurement of the changing escaping infrared radiation. Where this handful of climate scientists disagrees with the heavy majority of their colleagues is in the value of the climate sensitivity. They maintain that negative feedbacks (see Lesson 2) counteract the direct forcing of the increased CO_2 so that the climate sensitivity is very small—say only about 0.7 ^oC for a doubling of CO_2, very much less than the value of 3-4 ^oC illustrated above and advocated by nearly all climate scientists. In fact, the latest assessment of the equilibrium climate sensitivity is that it is ***very unlikely*** to be less than about 1.6 ^oC, still well above 0.7 ^oC.

2) The second reason to discuss climate sensitivity in detail is that it tells us what is in store for us in terms of temperature increase for whatever level of CO_2 the world finally chooses to allow. And the global temperature of the atmosphere and oceans will ultimately control all the other aspects of climate change we will discuss in **Lesson 9 Impacts of Climate Change**.

So, how is the climate sensitivity estimated? Basically, there are two approaches:

1) With a climate simulation model (like the one used to generate Figure 1), introduce a forcing by quickly doubling the amount of CO_2 in the atmosphere. The increase in the temperature that finally results is around a value of 3-4 degrees centigrade for doubled CO_2. The advantage of this approach is that one can make various changes in the climate models to see how critical the various inputs to the model are. The disadvantages are that a) The models need to be run to simulate at least 1000 years of real time in order to let the climate come nearly to equilibrium and this takes a lot of expensive computer

time. b) One can never be sure that some important feedback has not been accurately represented in the computer model or even that an important feedback has been left out altogether.

2) A second approach is to let the Earth be our computer! This approach can itself be divided into two categories depending upon the time intervals over which observed changes in the Earth's temperature can be compared with the observed or estimated forcing. If the interval is short compared to the time taken for equilibrium to be established, say a matter of one or two decades, then the sensitivity being measured is more relevant to the transient sensitivity whereas if the interval of time is much longer, then an estimate of the equilibrium sensitivity is obtained.

An example of the former—a short term response to 'forcing'--is the analysis of the global temperature response to recent solar cycles of the last 4 decades. (Tung, Zhou & Camp: Geophysical Research Letter: L17707, 2008). Similar estimates have been made when the short-term forcing involves the cooling due to volcanic eruptions.

At the other end of the timescale—using data from as "recent" as 20,000 years ago during the last glacial maximum to much longer ago in the past—up to 65 million years ago-- changes in the temperature and other conditions in the climate system can be used to estimate climate sensitivity.

Such estimates involve the use of the concept of 'forcing' in a slightly different way than we have defined it in Lesson 2. There, we considered 'forcings' to be processes affecting the climate system through altering of the Earth's energy balance, but without these 'forcings' themselves being affected by resultant changes in the climate system.

However if we are interested in obtaining information from paleoclimate studies in order to supplement estimates based upon computer simulations for what is likely to happen during the next 100 years or so (when the CO_2 content may double or triple from its preindustrial value of about 280), then it is important to distinguish between those feedbacks that are "fast"—like water vapor and sea ice feedbacks from those that act much more slowly. Examples are major changes in the Greenland and Antarctic ice sheets and major changes in the vegetation covering the Earth's surface taking considerably longer than the 100 years of interest. In this case the slow feedbacks must be compensated for to study how the temperature responds when only fast feedbacks act.

Additionally, it is dubious to use data from eras when the Earth's climate was very different from what it is today if, again, we are interested in obtaining information about climate changes in the next 100 years in response to increased forcing from doubling or tripling of CO_2.

A recent analysis of paleoclimate data by a consortium of paleoclimate scientists who carefully addressed these considerations concluded that in fact the

paleoclimate data support estimates for the ‘fast’ climate sensitivity that has a value of about 3.5 ^oC for doubled CO_2.
(As reported in Nature, Vol. 491, November 2012, pp 683-691).

When one assembles various estimates of climate sensitivity that do ***not*** utilize paleoclimate data, they also center on values of about 3-4 ^oC but with a small probability of the true value having a slightly smaller value and a small probability of the true value extending to a somewhat higher value. The rough agreement between the paleoclimate estimates and both the computer simulations and estimates from current very recent climate changes gives some confidence that the estimates of climate sensitivity are not wildly off. The following figure, taken from http://www.skepticalscience.com/detailed-look-at-climate-sensitivity.html summarizes the situation. It gives three different estimates of the probability that the true equilibrium climate sensitivity has some particular value. The link above contains a more detailed but very readable account of climate sensitivity.

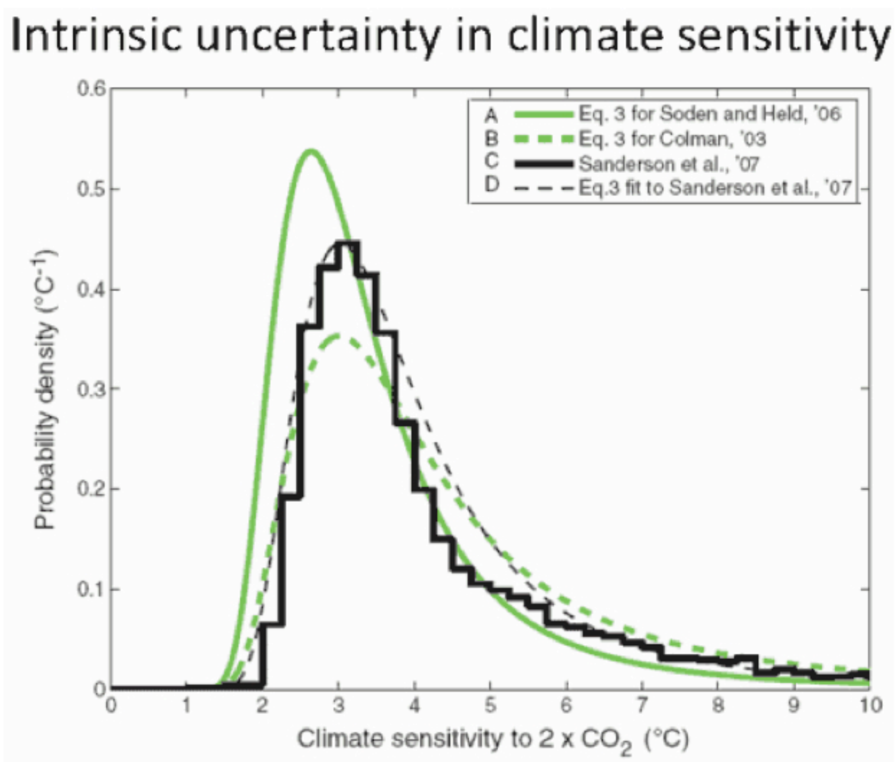

Figure 3.
An estimate of the probability that the equilibrium sensitivity takes on any particular value. See the link above for details.

Note that the very low value advocated by the very small number of climate scientists mentioned above, occurs at a value with a vanishingly small probability according to the analyses represented in this figure.

After this lengthy discussion, one may ask: why not carry out the most obvious determination of the transient sensitivity: after all, we know very accurately the rate at which CO_2 has been accumulating over the last 50 years or so and only slightly less accurately previous to that: why not simply look at how the global temperature has responded to increasing CO_2 during the last 50 years or so? The answer is in fact that this has been done, and the results are not inconsistent with the graph above. However it is not as simple as that. One needs to remove the effects not only of variable external forcings such as the solar cycle and volcanic eruptions, but natural internal variability associated with quasi-episodic events like El Nino-La Nina. Even more importantly though, a very significant forcing--mostly negative--has varied over the last several decades and is still only very imperfectly measured: namely "aerosols", the small solid particles some of which ***trap*** heat (soot) but more of them ***reflect*** heat and thus act to partially offset greenhouse gases. In fact, very recently it has been suggested that the aerosols produced in China by combustion of coal has had a significant impact on recent global temperatures, but the amount is still difficult to quantify.

So, for these reasons the seemingly straightforward estimate is not quite so straightforward as would appear at first glance.

One final cautionary, one might even say ominous, remark: We have emphasized the value of climate sensitivity appropriate for times of about 100 years into the future--before the slow feedbacks have had time to respond to increased CO_2 forcing. When paleoclimate data from eras with a climate not very dissimilar to our present one are analyzed, one of the studies cited by the paleoclimate scientists discussed above suggests that when ***slow*** feedbacks have enough time to act, the long-term equilibrium climate sensitivity may be much larger—perhaps almost double the "fast" value. In view of the long residence time of the increased CO_2 we are putting into the atmosphere, this is a rather sobering result for it would result in a temperature increase ***above*** today's value of about as much as the temperature during the depth of the last ice age was ***below*** today's value.

This completes the background of basic concepts of climate science. In Lesson 9 we explore the effects already being seen in a warming world and those that are projected to occur over the remainder of this century. These effects alter not only the physical state of the climate itself but will almost surely affect human society and the rest of the environment in profound ways.