Central Coast Climate Science Education

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Lesson 8: Climate Sensitivity

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In this next-to-the-last Lesson we take up the following question: Given some process which acts to disturb the energy balance of the climate system, how much will the global surface temperature increase. The process which 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 question we consider in this Lesson is: How much will the global surface temperature increase?

The concept of ***climate sensitivity*** was mentioned briefly in Lesson 2. 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 there are other forcings besides carbon dioxide so the concept of climate sensitivity is generalized to include the temperature rise resulting from the forcing from other sources (for example, changes in the sun's brightness) equivalent to a doubling of the carbon dioxide.

One might have imagined that the climate sensitivity depends very strongly on which forcing mechanism is acting. However, this does not seem to be the case, though the details of the distribution of the resulting temperature increase over the various parts of the world and with altitude in the atmosphere do. A prime example of such a detail is the change in temperature of the stratosphere, the layer of the atmosphere above the troposphere. In the troposphere the temperature drops steadily with altitude, but in the stratosphere begins to rise again due to the absorption of ultraviolet solar radiation by the ozone layer. An increase in 'forcing' due to an increase in solar radiation will increase the heating via this mechanism, and thus warm the stratosphere. However an increase in the forcing associated with trapping of energy by increased concentration of greenhouse gases will result in stratospheric cooling as less of the infrared energy emitted by the Earth reaches the stratosphere where it can be absorbed by CO_2

The concept of climate sensitivity is not meaningful unless one also specifies how quickly and for how long the forcing is applied, and, crucially, how long afterward one waits to see how much the temperature will have risen. 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!

If, for example, one were to assume that the Sun were to increase its brightness by 0.3%--a very large increase when one considers that this is about 4 times as much as the change between its minimum and maximum brightness during the course of the sunspot cycle--then we know that ultimately the Earth would surely end up being significantly warmer as it came back into energy balance. The Earth will emit more infrared radiation until that increased emission has balanced the increased input from the Sun.

Climate scientists define the ***equilibrium* climate sensitivity** as the ultimate resulting temperature increase if the forcing agent is quickly 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 large range in CO_2 concentrations the forcing increases by about the same amount for every doubling of the CO_2 concentration: specifically, by about 4 watts per square meter.

Figure 1, 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. (Of course there is no moment when it is exactly established, but it 'asymptotically' approaches equilibrium.) 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 that after 100 years the time axis is 'stretched out' and plotted on a logarithmic scale.

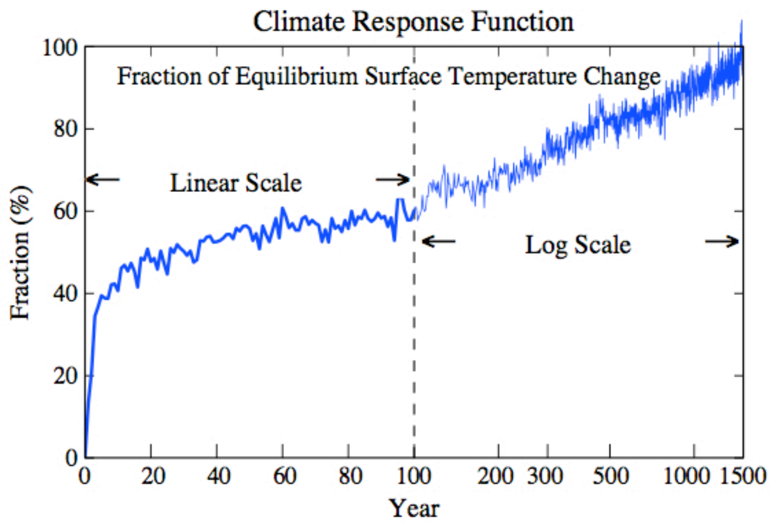

Figure 1. The approach to the final change in surface temperature after a forcing is introduced. Note that even after 100 years the temperature has warmed only 60% of its final equilibrium value.

On the other hand the ***transient* climate sensitivity** refers to 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 because of the large 'thermal inertia' due to the huge heat capacity of the ocean, the short term, or transient, temperature increase is significantly less than the equilibrium response--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.

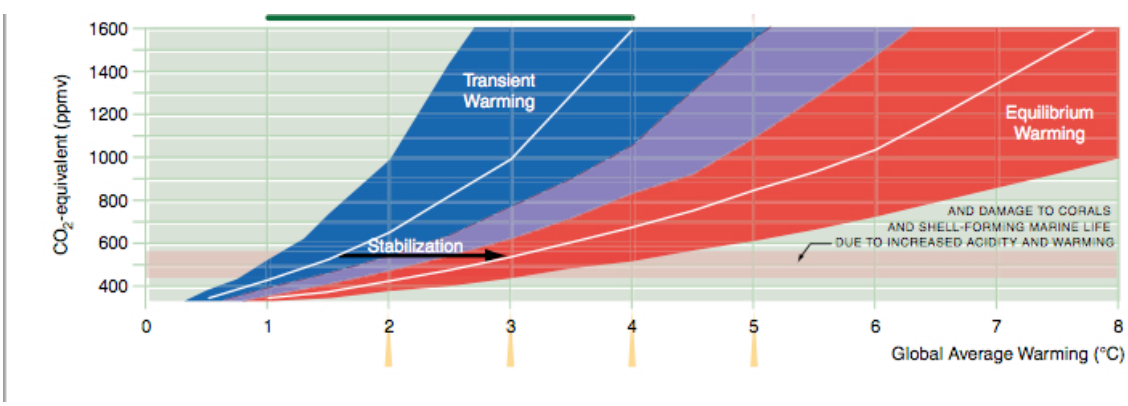

Figure 2. The blue area shows the range of estimated transient temperature responses to various levels of CO_2 concentrations, while the red area shows similar estimates for equilibrium temperature responses. The two white lines are the best estimates for these two ranges of estimates.

The current CO_2 concentration is nearly 400 ppm and is rising at about 2 ppm each year. The current temperature (compared to the value prior to the rapid CO_2

increase marking the industrial revolution) is about 0.8 ^{o}C. As the forcing is continually increased and the CO_2 concentration has risen to 800, then the midrange estimate for the temperature (the white line in the blue portion of the figure) is about 2.4 ^{o}C, or an increase of about 1.6 ^{o}C. However if the concentration is then fixed at 800--i.e. doubled from 400--the warming will continue until a new equilibrium is reached, whose midrange estimate (the white line in the red portion of the Figure) is a temperature of about 4.8 ^{o}C or an increase of about ^{o}3 C, in which case the equilibrium climate sensitivity is 3 ^{o}C.

We have gone through this in some detail for the following reason: Among professional climate scientists, about 97% are of the opinion that human activities have caused and will cause a significant warming of the Earth's climate and that the associated impacts of this change 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 and moreover is confirmed by direct measurement of the changing escaping infrared radiation by satellites. Where this handful of climate scientists disagrees with the heavy majority of their colleagues is in the value of the climate sensitivity. They claim 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 ^{o}C for a doubling of CO_2, very much less than a typical value of 3 ^{o}C illustrated above.

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. Increase the Sun's brightness as described, or double the amount of CO_2 in the atmosphere. The results center around a value of 3 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 about 1000 years of real time in order to let the climate come 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 a few thousand years 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, the net forcing between ice age conditions about 20,000 years ago and the pre-industrial conditions lead to estimates of the equilibrium climate sensitivity. (J. Hansen & M. Sato: in preparation). Such an estimate involves 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 the Earth's energy balance, but without these forcings themselves being affected by resultant changes in the climate system. In the estimate of climate sensitivity by Hansen & Sato, the difference in the albedo of the Earth due to the change in ice coverage and vegetation between the depths of the ice age 20,000 years ago and the situation at the start of the industrial revolution gives rise to a change in energy input, and this is taken as "given"--a forcing rather than as the very slow feedbacks which they actually are. Similarly, the large increase in CO_2 from 20,000 years ago to just prior to the industrial revolution is regarded as a forcing: again it is really a slow feedback. (These changes are of course natural, in contrast to the very rapid human-caused increase in CO_2 which really is a forcing as we have defined it in Lesson 2.)

In the work of Hansen and Sato, it is estimated that the change in energy input due to the change in albedo is 3.5 watts per square meter, with an additional 3.0 watts per square meter due to the increased trapping of infrared radiation from the increased CO_2 for a total of 6.5 watts per square meter. Over this interval of 20,000 years these same authors deduce an increase in global temperature of 5 ^{o}C based on paleoclimatic records. So the temperature increase per 1 watt per square meter of forcing is 5.0/6.5 or about 0.75 ^{o}C for every watt per square meter of forcing. Since the climate sensitivity is usually characterized as the amount of temperature increase for a doubling of the CO_2 concentration, which results in increased forcing of about 4 watts/square meter. Multiplying the 0.75 by 4 gives this "paleo" estimate of climate sensitivity of about 3.0 ^{o}C. Of course this forcing took place gradually as the ice age gave way to the Holocene era which began about 10,000 years ago, but since then the climate has been quite stable on a global scale and has had ample time to come to equilibrium. So this "paleo" estimate is an *equilibrium* sensitivity estimate. This response of temperature to the forcing just described takes account of the important 'fast feedbacks' involving sea ice, clouds, water vapor and ocean circulation, (though some of these are 'slow' compared to the decades over which humans have changed the CO_2 concentration in the atmosphere.)

When one assembles all the various estimates of climate sensitivity (with attempts to convert the transient sensitivity estimates to equilibrium sensitivity estimates), they in fact center on the same value of 3 as the paleo estimate above, but with a small 'tail' toward slightly smaller values and a larger 'tail' extending to higher values. The following figure, taken from http://www.skepticalscience.com/detailed-look-at-climate-sensitivity.html summarizes the situation. This link contains a more detailed but very readable account of climate sensitivity.

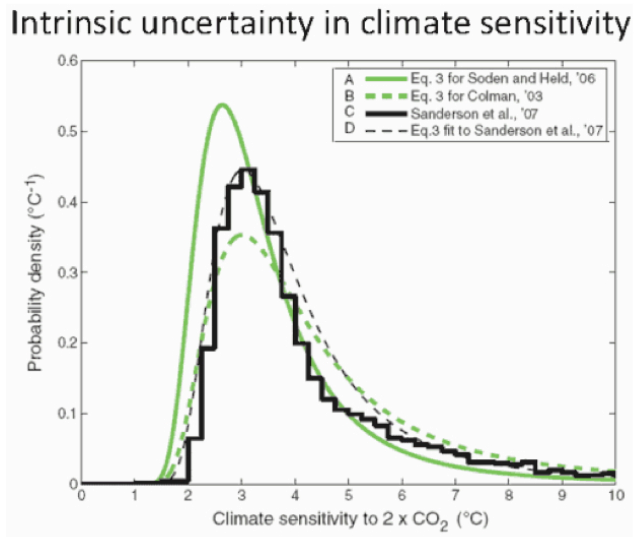

Figure 3. An estimate of the probability that the equilibrium sensitivity takes on any particular value. See the link above for details.

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. The answer is in fact that this has been done, and the results are consistent with the graph above. However it is not quite 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 imperfectly known: namely aerosols. So, for these reasons the seemingly straightforward estimate is not quite so straightforward as it would appear at first glance.

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