Central Coast Climate Science Education

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Lesson 5: Is The Earth Currently in Energy Balance?

With the background provided by the previous four Lessons, we are now able to address the fundamental question of whether the Earth's climate system is in energy balance. The Earth's climate system is a complex one, comprised of the land surface, atmosphere, ocean surface, deeper ocean layers, the 'cryosphere' – mountain glaciers as well as the sea ice and massive ice sheets of Greenland and Antarctica -- and the biosphere.

Let us quickly review the important points of the first 4 Lessons:

In ***Lesson 1*** we described the basic concept of energy balance: Measure the total amount of sunlight falling on the Earth, then subtract the amount of reflected sunlight and the amount of infrared radiation that escapes from the top of the atmosphere: If the result is a positive quantity, the Earth's climate system is gaining energy; if it is negative then it is losing energy.

In ***Lesson 2*** the concepts of '***forcings'*** and '***feedbacks***' were described: ***forcings*** are those processes which affect the Earth's energy balance but which are themselves unaffected by how the climate system reacts. Changes in the Sun's brightness and human production of infrared-trapping gases are two examples. ***Feedbacks*** are processes in the climate system reacting to forcings. If a feedback reinforces the forcing, it is a 'positive feedback'. Melting ice and snow caused by warming from a 'forcing' exposes more of the land and ocean surface that absorb more sunlight instead of reflecting it, increasing the warming, causing more melting -- and so on. This is an example of a positive feedback.

In ***Lesson 3*** the Greenhouse effect was discussed. The distinction was drawn between water vapor, which acts as a feedback process and ***human-generated*** carbon dioxide, which is a forcing process. Both reduce the amount of infrared radiation given off from the surface of the land and ocean that is able to escape into space.

Finally, in ***Lesson 4***, the distinction between short term effects ("weather") and long-term averages over the weather ("climate") was made. It was pointed out that processes in the atmosphere and ocean, like El Nino, should really be considered "weather". Such processes are at best difficult (and probably impossible) to calculate accurately many years in advance. This is only partly because they are not yet fully understood and because of limited spatial resolution in the computer models. It is likely that they exhibit the kind of 'chaotic' behavior described in Lesson 4 and illustrated by a turbulent stream of water. These effects contribute to what climate scientists refer to as 'internal natural variability' and require averages over several decades in order not to be misled by variability of a few years duration.

From the material in Lesson 1 it would seem a simple matter to give a straightforward answer to the question 'Is the Earth's climate system in energy balance'? All one need do is "simply" measure from orbiting satellites: the amount of incoming sunlight, the amount of reflected sunlight, and the amount of escaping infrared radiation.

Unfortunately, this is not so simple. Different instruments on the satellites measure these quantities and putting them on a common energy scale is not easy. Moreover, the incoming energy from the Sun comes to us from a very specific direction in space, while the reflected and infrared radiations must be measured over the entire globe. Furthermore, from any one spot on the Earth, the reflected radiation is diffused over wide angles. All of these considerations are made more difficult by the fact that only a small imbalance seems to be present, though that imbalance is sufficient to significantly change the Earth's climate if it persists over decades, as it now seems virtually certain to do.

Nevertheless, various research groups have analyzed the data from these satellites. They seem to be converging on the result that the Earth, over the last few decades, ***is*** out of energy balance: The Earth is sending back into space roughly 0.3% less energy than we are receiving from the Sun, though that number is not accurately known because of the uncertainties described above.

What has happened to this energy? The answer to this question provides another approach towards answering the basic question of whether the Earth is in energy balance: Here is the figure from Lesson 1 again:

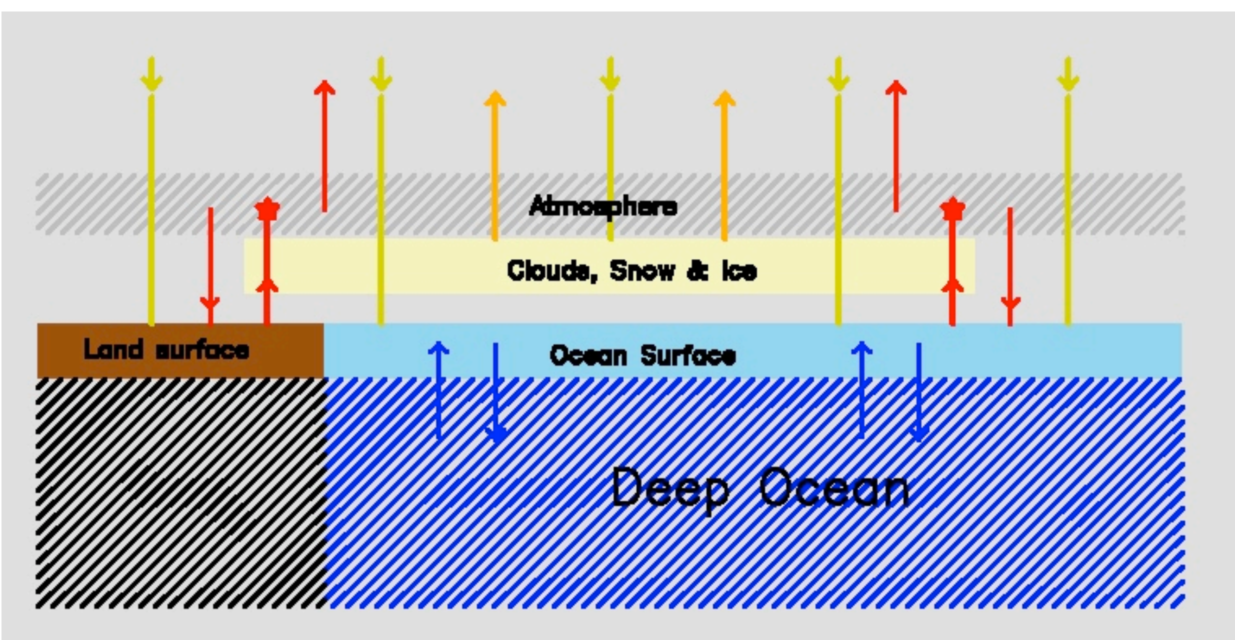

Figure 1

In Lesson 1 we used the analogy of a bank account, with the incoming sunlight representing gross income, (yellow arrows) the reflected sunlight (orange arrows) representing the loss due to taxes, and the upper two red arrows the net expenses. To push the analogy further, the land surface and ocean surface could represent a checking account that fluctuates with month-to-month income and expenditures, while the deep ocean represents a savings account that gradually accumulates funds if our business is profitable. If the accounting during the year were rather sloppy the monthly incomes and expenditures might not be accurately known, but the year-end 'bottom line' is whether you have been able to add to the savings account or have had to withdraw from it.

In the Earth's climate system, the land and ocean surface and the atmosphere are the 'checking accounts', while the deeper ocean is the savings account. The physical reason for the distinction is that the land surface and the superficial ocean layers and the atmosphere do not have much 'heat capacity' while the deeper ocean does. (For a wonderful simple demonstration of this concept see the short JPL video clip “Oceans of Climate Change” http://tinyurl.com/yjojgyl)

As discussed above, the analyses of the Earth's energy budget leads to the result that the Earth has, ***averaged*** over the last few decades, and ***averaged*** over its surface, been gaining more energy than it has been radiating away. This amounts to very roughly 0.8 watts for every square meter of the Earth's surface. (A watt measures the rate at which energy "flows" or is being converted from one form to another. A light bulb converts electrical energy into heat and light at the rate of 100 watts.) Thus this amount of energy imbalance over every square meter is less than 1% of the rate of energy consumption by an ordinary 100 watt bulb. (A square meter is about 10 square feet).

But, since there are a ***lot*** of square meters over the entire Earth, this adds up to a lot of energy over a fairly short time. What has happened to all that energy? Some has gone into an increase in the heat stored in the land, atmosphere, and surface layers of the ocean. But most of it has been stored as heat in the ocean. Be careful though, to distinguish between an increase in ***heat energy*** from an increase in ***temperature***. Even though there has been a huge increase in the heat energy of the deep ocean, because of its huge heat capacity the actual increase in temperature is not large. The above video demonstrates this nicely.

How do climate scientists know that the ocean has been storing up this energy? Because it has been measured. One way this is done is to drop probes which sink into the depths of the ocean and on their way down radio back the temperature at each depth. It is a simple matter to then convert this temperature at each depth to the amount of energy stored at each depth. Here is a graph of how the energy content of the ocean has ***changed*** since 1950. Notice how it dwarfs that in the land and atmosphere. (Of course, the change in the energy in the atmosphere is what gets the most attention, and we will discuss global air temperature trends as well.

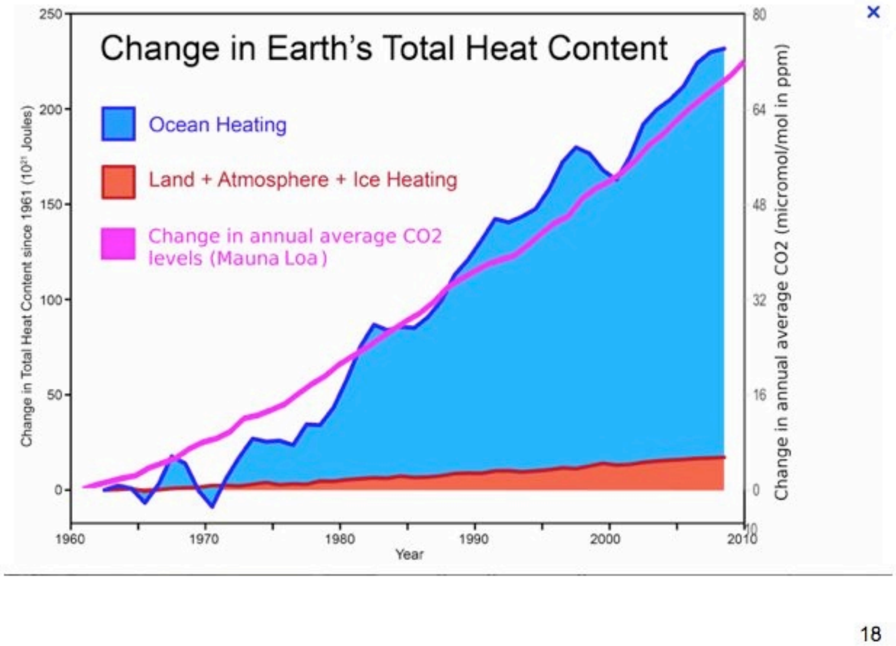

Figure 2

Notice that it is not a regular increase every year -- sometimes it drops a bit because of the 'weather' that occurs in ocean currents and mixing of water between shallow and deeper waters. But since 1970 there has been an unmistakable upward trend.

A striking way to grasp how large this energy storage has been since 1970 is to consider a large nuclear power reactor such as one of the two operating at Diablo Canyon on our California Central Coast. Each of those reactors generates a little more than one billion watts at full capacity. That is enough to keep 10 million 100-watt light bulbs burning continuously. Suppose those billion watts were instead diverted into heating the ocean. How long would it take to increase the heat energy in the ocean by the same amount that has occurred over the last 40 years from the very slight energy imbalance of the Earth? It is a simple calculation to make, and the answer is about 6 million years!

Or, here is another way to bring home the enormous energy storage resulting from the seemingly small energy balance: When we get our electricity bills, we are charged a certain rate (or set of tiered rates) for each KWH of electricity used. A "KWH" is a kilowatt-hour: the amount of energy used up in one hour when you are using electricity at the rate of 1000 watts. The energy stored in the deep ocean since 1970 represents about 60 quadrillion (60,000,000,000,000,000) KWH. How would you like to get a bill for that from your power company!

Between 1950 and 1970 climate scientists did not have the whole array of satellites and other observing systems in place and it is not certain what caused the decline in heat content between about 1958 and 1970. There was one significant volcanic eruption in that period that probably contributed to some cooling. Also, relative to the situation from 1970 onward, when the U.S. and Europe began controlling air pollution, the cooling forcing from man-made aerosols was likely more important relative to greenhouse gas forcings than it is today.

To summarize to this point: satellite measurements of the energy imbalance of incoming and outgoing radiation, together with the increase in heat energy stored in the ocean, constitute powerful evidence that the Earth has been out of energy balance for the period of the last 4 decades when accurate observations from satellite and other techniques became available.

So, the obvious question is: Which of the forcings we described in Lesson 2 are most responsible? Always keep in mind that we are asking about the ***changes*** that have occurred in the various forcings in recent times. There must have been many centuries when the Earth must have been very closely in energy balance compared to the imbalance today. If this were not the case, there would have been far more dramatic changes in the Earth's climate than we have been starting to see over the last few decades. To be sure, there have been climate swings, including the 'medieval warm period' and the 'little ice age' but these have been small ***averaged over the globe***, compared to what we are now starting to experience.

Over these last few decades there are only four forcings that can vary rapidly enough to act in such a short time. (A review of Lesson 2 might be helpful to some readers here). These four are:

1) Variations in the Sun's energy
2) Temporary cooling for a couple of years due to major volcanic eruptions
3) Cooling due to man-made aerosols
4) Heating due to trapping of infrared radiation by increased greenhouse gas emissions

Here is a record of the Sun's brightness as measured by two NASA satellites. The one currently in orbit is SORCE.

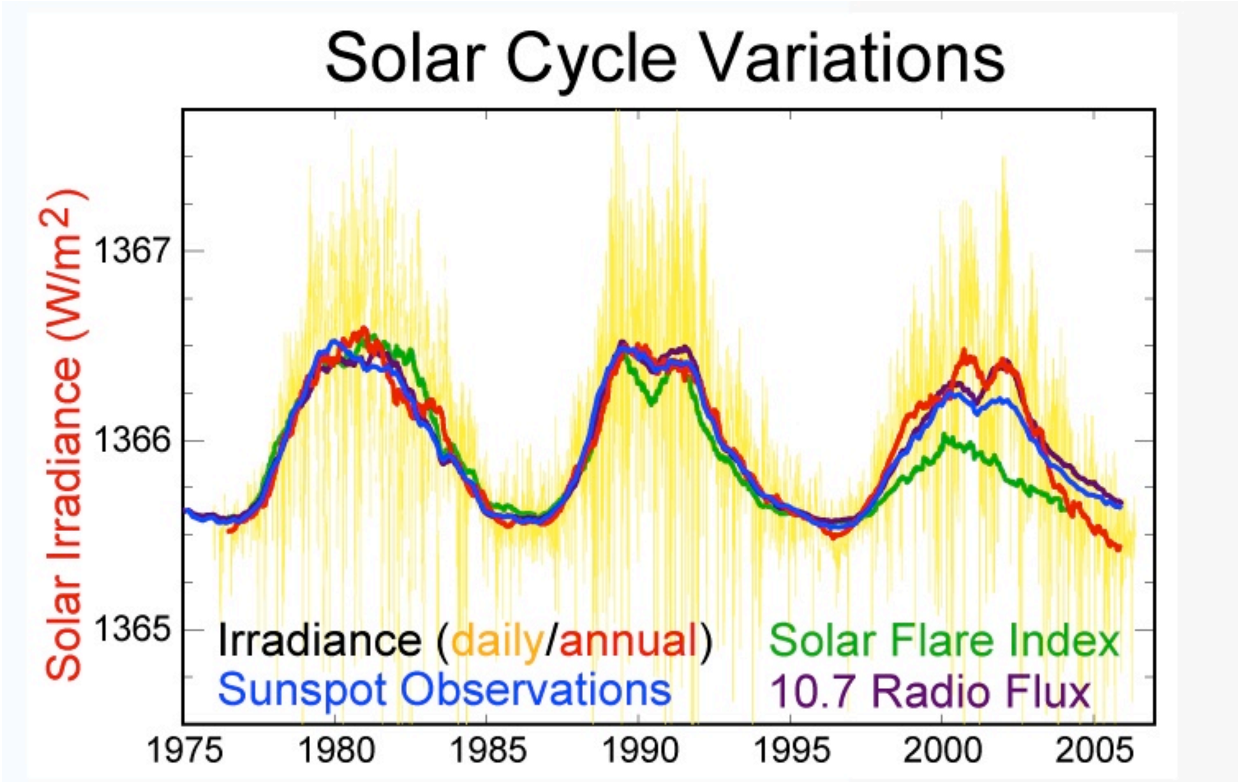

Figure 3

The curve to pay most attention to is the red curve that gives the best average measure of the Sun's radiation received by the Earth since 1975. Although it may seem as if there is a large variation, this is because the graph just shows the amount by which the sun's direct brightness changes -- from about 1365.5 to 1366.5 watts per square meter. This is a change of less then 0.1%. If the plot were shown running from 0 to 1367, the change in brightness would not be visible. Nevertheless, even this small change can be detected in the changes of global temperature. The important thing to notice, however, is that there has been no ***average*** change in the Sun's energy over this period. If anything, there has been a very slight **decrease** in this ***average*** energy. Thus, the Sun has not been responsible for the energy imbalance over the last few decades.

The second possible "forcing" that should be examined involves the cooling due to volcanic eruptions. A major eruption occurred in 1991, when Mount Pinatubo erupted in the Philippines, sending tremendous clouds of material up so far into the stratosphere, that it took a couple of years before most of the material gradually settled back to Earth. This eruption caused an easily measured **cooling** in the average global temperature for about two years.

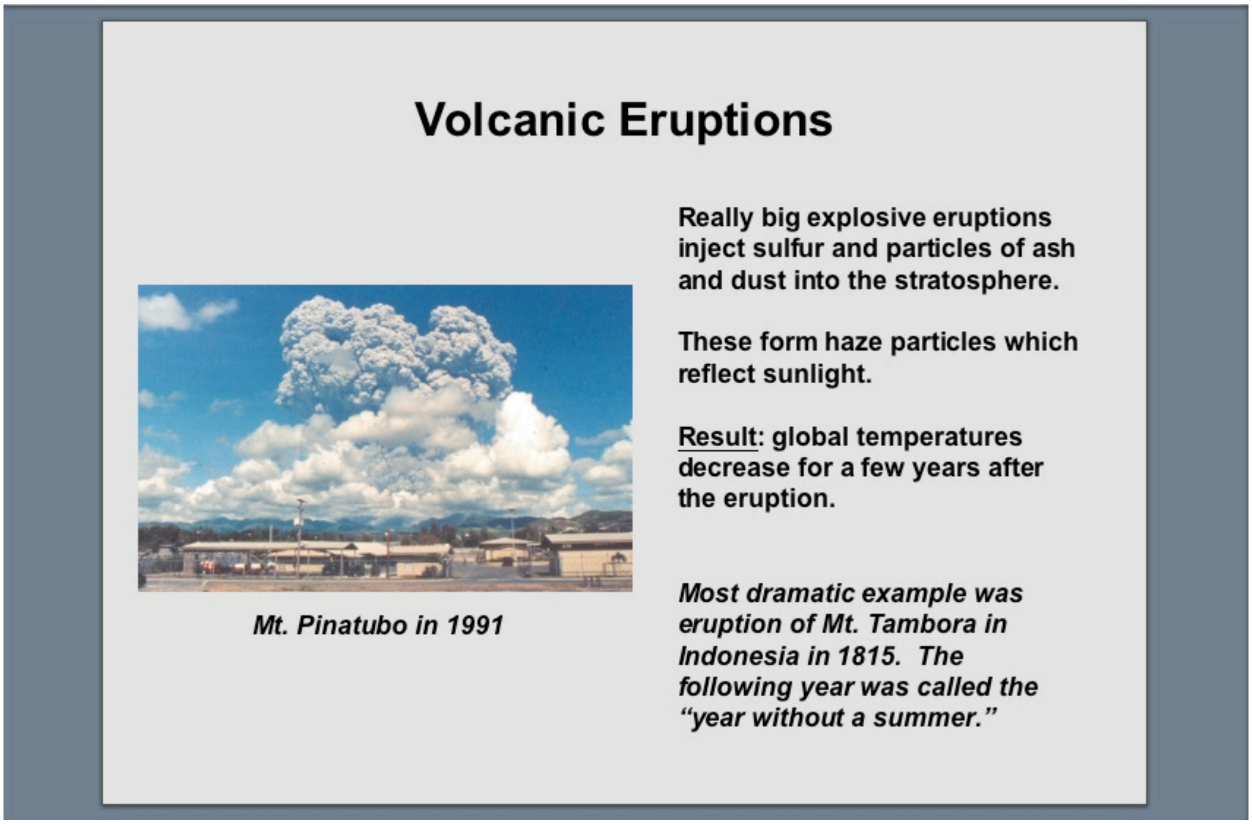

Figure 4

The two remaining important forcings over the last few decades are both man-made: a) The emission of carbon dioxide and other greenhouse gases b) The emission of small particles ("aerosols") which come in a variety of forms, some of which are heating forcings but overall they act to cool. The increase in greenhouse gas emissions has been quite accurately measured and the heat trapping effect can be quite accurately calculated, as discussed in Lesson 3. However, both measurements and calculations for these man-made particles are much more difficult. Therefore, it is hard to know exactly by how much they are offsetting the warming from the greenhouse gases we are putting in the atmosphere. But it is hard to escape the conclusion that the observed energy imbalance in the Earth's climate system that has been observed in the satellite era is due primarily to the emission of greenhouse gases and to a lesser, but significant amount, by deforestation.

Attribution Studies

Now that we have described the energy imbalance in the Earth's climate system and reviewed the forcing functions that have contributed to this, what conclusions can be drawn about the relative importance of each? Studies aimed at answering this question are called 'attribution studies'. Most of these studies rely on computer simulations, while others do so only to a limited extent. An example of the latter is shown in the set of graphs below: The top graph has a black curve and an orange curve. The black one is the ***change*** in global air temperature from 1980 to 2008 ***relative*** to the 'base period' 1951-1980.

(Remember though, that global air temperature changes only involve a very small portion of the climate system's total heat capacity. Indeed there may be periods when energy exchanges between the atmosphere and ocean result in some global air temperature cooling, (especially involving large El Nino or La Nina oscillations),
even while the full climate system continues to gain energy.

The orange curve results from taking the combination of the volcanic and solar forcing functions and the internal ENSO oscillations that come closest to reproducing the observed global temperature for the 1980-2008 period. We will describe the orange projection into the future below.

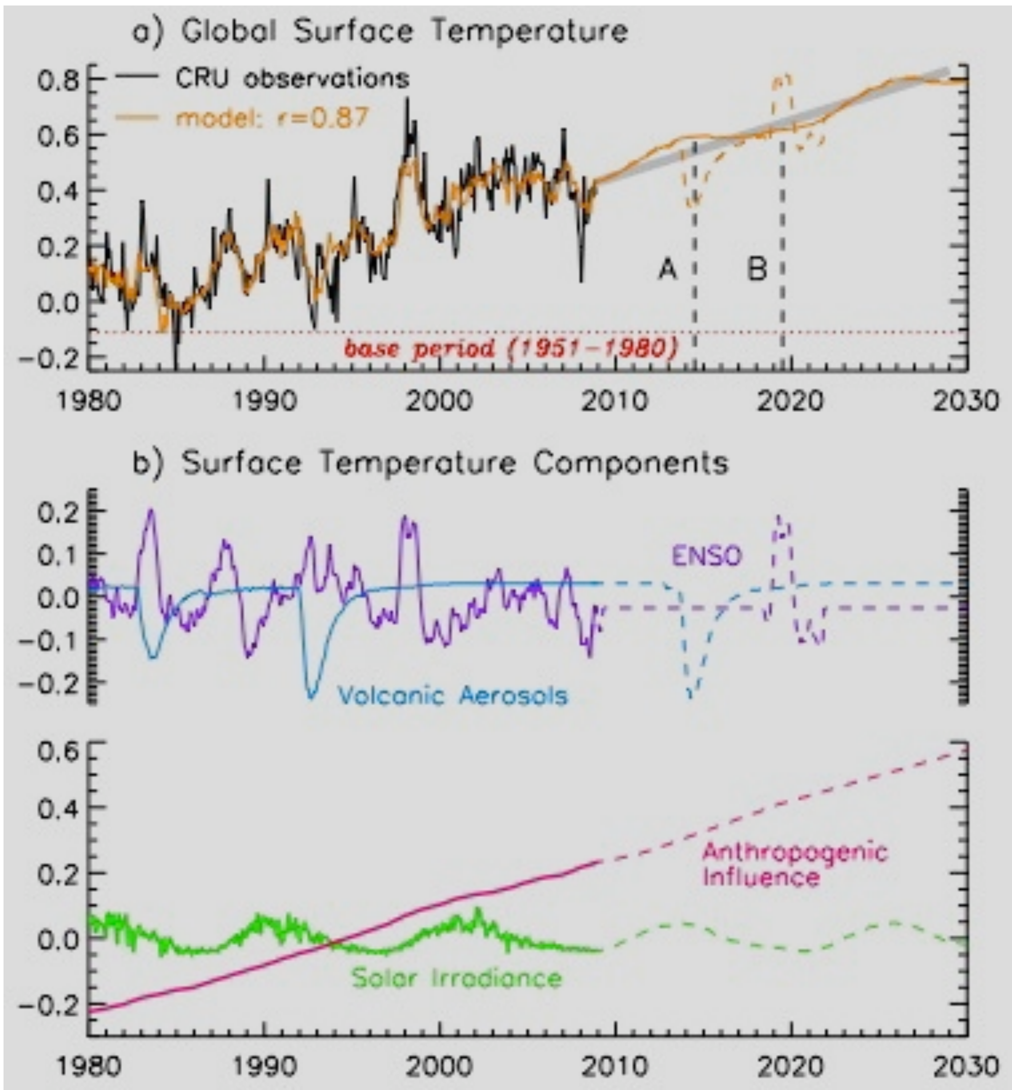

Figure 5

In the second graph, the purple curve shows the portion of the observed temperature which is attributed to the "ENSO" (El Nino) oscillations: Remember that ENSO is not a true forcing function but it does cause marked ups and down in the global temperature -- i.e. it is the kind of long term 'weather' ("natural internal variability") we previously discussed. It is responsible for the wiggly ("noisy") character of the black curve in the plot above with the orange and black curves.

An especially strong El Nino caused a spike in the global temperature record that is the reason1998 was unusually warm. The blue line is the cooling forcing from volcanoes and the cooling that resulted from the 1991 Pinatubo eruption is easily seen. The forcing due to the solar sunspot cycle is shown in green. Finally, the ***difference*** between the **warming** from greenhouse gases and the **cooling** from human particulates is shown in pink. Recall that it is difficult to accurately measure the effect of the human particulates, but the net effect of the human forcing has clearly been to add heat to the climate system. Adding up the purple, blue, green and pink contributions in the amounts shown produces the orange curve that matches fairly well the observed black curve.

Assuming that the solar cycle continues pretty much as it has, projecting the increased greenhouse gas forcing based upon expected energy consumption, and assuming that aerosols continue to cancel out about the same fraction of greenhouse gas warming as they now seem to (roughly 50%), one can project what the next few decades are likely to bring. This is the basis for the extension of the orange curve. Of course no one can predict with certainty when the next major El Nino event will occur, or when the next major volcanic eruption will occur. For illustrative purposes a major eruption has been assumed to occur in 2015 (point A) and a major El Nino event has been assumed to occur in 2020 (point B), and their influence on the future temperature record is what the dotted orange curve shows.

The main message to be taken from all the attribution studies carried out recently is this: ***greenhouse gas forcing is now dominating our climate and will continue to do so more and more***. The influence of the solar cycle will still be detectable as will volcanoes and El Nino events, **but they will be overwhelmed by the greenhouse gas forcings unless a major reduction in fossil fuel use occurs.**

In Lesson 8 ("Impacts of Continued Climate Change") we will consider some of the current and future consequences of the Earth's energy imbalance and the accompanying increased energy storage and warming. First, however, we need to talk about another important part of the climate system that, like energy, is out of balance. This is the 'carbon cycle' and we will discuss "The Carbon Cycle" in Lesson 6. Before we begin the 8th Lesson on impacts, there is still another Lesson to be learned: Lesson 7: "Looking Forwards by Looking Backwards" explores the science of Paleo-Climatology. It deals with what studies of the Earth's climate in the past -- the Ice Ages of the last few hundred thousand years, and the climate going back even tens of millions of years -- can tell us about our climate of today and in the future.

<u>Addendum: Comment on “has the Earth stopped warming”?</u>
A frequently heard myth is that “the Earth has not warmed since XXXX”, where XXXX is frequently taken to be 1998. There are several problems with this assertion:

* It arbitrarily chooses as a starting point 1998--the year in which a very strong El Nino caused a spike in the global air temperature.

*More importantly, only by looking at longer term periods and averaging out the fluctuations due to El Nino/La Nina oscillations, the solar sunspot cycle and volcanic eruptions, can one gain an accurate picture of any long term trend.

The following graph is based on four separate globally-averaged land surface temperature records using a “10 year running average”—i.e. any point on the graph represents the average global temperature extending 5 years on either side of that point. In this graph, therefore, the last point (about half way through 2006) incorporates data though 2011.

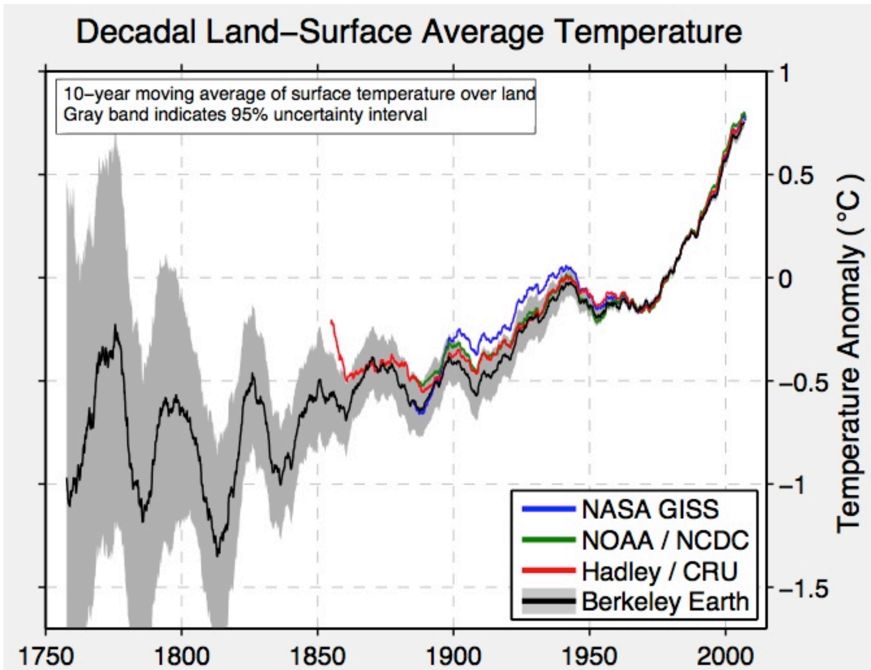

Figure 6

Note the following points: a) The gray shaded parts of the graph are an indication of the uncertainties in these global averages. Prior to 1850 or even somewhat later, the quality and quantity of the observations was so poor that discerning any trend is rather questionable. b) Four different groups all get very similar results, especially after 1950 when the quality and quantity of the data improved. c) Finally, and most importantly, there is no indication whatsoever in this long-term trend that “warming has stopped since 1998”.

Finally, as was emphasized above, most of the heat storage resulting from energy imbalance in the Earth’s climate system goes into the ocean. Recent measurements of the ocean heat content are greatly improving, both by sampling more of the ocean all around the globe, but also by measuring the energy accumulating in the ocean down to greater depths. In the following figure, depths down to 2000 meters (about two miles) are included. The figure below shows the result.

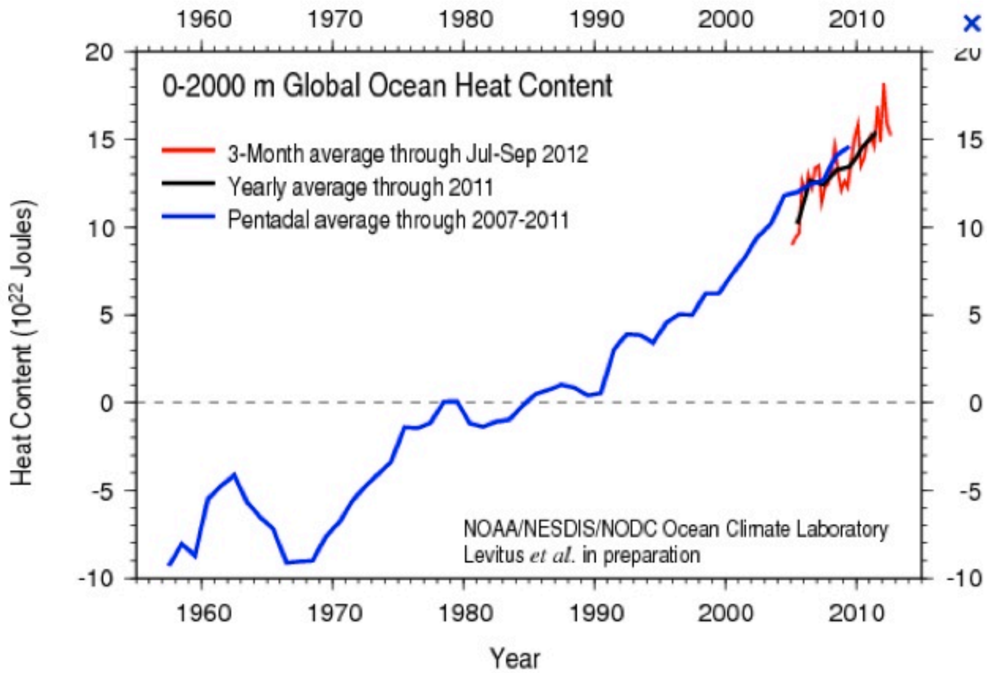

Figure 7

It is obvious from this figure that the accumulation of heat in the Earth's climate system has absolutely not "stopped since 1998".