Central Coast Climate Science Education

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Lesson 2: "Forcings" and "Feedbacks"

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In Lesson 1 we stated the basic law of energy balance, and how it applies to the Earth's climate system. The amount of incoming radiation from the Sun, minus the sunlight reflected back into space, and minus the infrared heat given off by the Earth which escapes back into space, gives the rate at which the Earth's climate system is gaining energy (if that difference is positive) or losing energy (if that difference is negative). In Lesson 5 we will examine the evidence for whether the Earth's climate system is currently in energy balance, and if not, whether it is gaining or losing energy. In this Lesson, we will first define and explain two very important concepts that Climate Scientists use to understand the Earth's climate: "Forcings" and "Feedbacks".

There is no precise definition for either of these two terms, but the following will suffice for our purposes:

Forcings: *Forcings* are *processes that affect the Earth's climate (or more specifically the Earth's energy balance) but that are not themselves affected by the changes in the climate change they induce.*

Six important forcings are:

- Changes in the Sun's energy output
- Slow changes in the Earth's orbit
- Volcanic activity (ash & gas)
- Continental drift ("plate tectonics")
- Human-produced changes in atmospheric composition and land use.
- Human production of tiny airborne particles ("aerosols")

Feedbacks: *Feedbacks* are *responses to the forcings that either augment ("positive feedback") or oppose ("negative feedback") the effects of the forcings.*

Four important feedback processes in response to a forcing are:

- Increase in water vapor as the Earth warms: water vapor traps heat, leading to further warming: (positive feedback)
- Increase in cloudiness with increasing water vapor as the Earth warms: some clouds reflect a lot of sunlight, opposing the forcing (negative feedback)
- Change in the reflectance of the Earth's surface as melting snow or ice is replaced by darker ocean or land surfaces (positive feedback)

- Release of CO_2 into the atmosphere as the oceans warm (positive feedback)

But see the addendum to this lesson

Notice that the use of the terms "positive" or "negative" do not imply "good" or "bad" responses as they do in common usage. If you have received "positive feedback" from your supervisor about a report that you wrote, that is good—but if you are concerned about global warming, then positive feedbacks are definitely not good news, since they enhance the effects of any increase in energy input from the forcings! Note also that a negative feedback in response to a warming forcing does not lead to overall cooling, but only reduces the amount of warming that would otherwise occur in the absence of the negative feedback.

Let us briefly consider each of these forcings and feedbacks in turn:

FORCINGS

Changes in the Sun's energy output:

Obviously this is a forcing, not a feedback. Whatever changes in Earth's climate are caused by changes in the Sun's energy output, these changes in the Earth's climate will not react back to cause subsequent changes in the Sun. We will comment on this particular forcing in some detail, since it has given rise to a lot of misunderstanding.

The first thing to point out is that there are ***two vastly difference time scales*** over which the output of the Sun changes: After the nature of the nuclear reactions deep inside the Sun were understood, it became possible to calculate how the Sun's brightness would change over billions of years as it's nuclear fuel is used up. Similar calculations can be made for other stars and compared with observations and the theory and observations are in excellent agreement. Climate scientists who want to understand how the Earth's climate has changed over geologic time scales (hundreds of millions of years) must, and do, take these changes into account.

If we are only concerned over times of hundreds of years the change above can be ignored—it is very small. However it is also well known that the Sun varies in brightness over the famous 11 year "sunspot cycle". The change in brightness between the maximum or minimum compared to the Sun's average brightness is very small—less than about 1/10th of one percent, though that small change is enough to have a detectable influence on the Earth's climate.

Moreover, it is not only the total brightness that varies, but also the relative amount of ultraviolet light, which influences the ozone layer in our atmosphere and the temperature structure high up in the atmosphere. In addition, as the Sun varies through the sunspot cycle there is a fairly good (but not exact) correlation between the strength of the "solar wind" that carries with it the weak magnetic field of the Sun. Just as the Earth's magnetic field shields us from much of this "solar wind", changes in the Sun's magnetic field cause changes in the degree of shielding in the solar system (including here on Earth) of the intensity of cosmic rays that originate at vast distances beyond the solar system. It has been suggested (but not widely accepted) that cosmic rays can act as important "seeds" for the production of droplets in clouds and influence the climate in this way. But the dominant effect seems to be the Sun's total brightness and any important role of the cosmic ray changes associated with the sunspot cycle has not been confirmed by further research.

As noted above, the long term changes in the Sun's brightness as it uses up its nuclear fuel are too small to be of importance even over a 1000 years. However, there is some evidence that there are changes in the Sun's brightness associated with changes in the strength of the sunspot cycle. So, a crucial question in trying to understand both the history and future of the Earth's climate over intervals of a 1000 years, is: Has the Sun's average brightness changed during the past several centuries, and will it change in the coming century or two? It is only over about the last 35 years that the Sun's brightness has been directly measured with the extremely high precision needed to quantitatively evaluate its role in recent changes in the Earth's climate. Go to the following link: http://earthobservatory.nasa.gov/Features/SORCE/ to learn about NASA's SORCE satellite ("Solar Radiation and Climate Experiment").

Slow changes in the Earth's orbit

These changes act very slowly and over the past and future 100 years or so and can be ignored over this time span. They are of special interest though, because they act as the "triggers" that have taken the Earth's climate system into and out of the several ice ages and "interglacial periods" that the Earth has experienced over the past several hundred thousand years. We will discuss the ice ages in Lesson 7.

Volcanic activity

Here again there are different time scales involved. Over very long periods of time (many millions of years) changes associated with continental drift can give rise to different levels of volcanic activity and over such ***very long periods of time*** the emission of carbon dioxide, the most important greenhouse gas, may be significant. Volcano scientists estimate that at present, the average amount of carbon dioxide produced by volcanoes **is less than 1% of that produced by human activities.** Over times of hundreds of years, the important effect of volcanic eruptions comes from the enormous amount of small sulfate particles ("particulates") that are ejected with such force that they stay in the stratosphere for a few years and can cause a significant increase in the amount of reflected sunlight. Thus, a decrease in the amount of sunlight reaching the Earth's surface results in noticeable cooling. The most recent such eruption was Mt. Pinatubo in the Philippines in 1991 that did cause significant cooling even when averaged over the entire globe. If there happen to be a larger than average number of eruptions in any given century, overall cooling is likely to occur, other things being equal.

Continental drift ("plate tectonics")

This is only of interest to climate scientists studying the very ancient history of the Earth's climate--the changes are much too slow to be of interest over times of hundreds of years. Continents literally drift around, change latitude and change ocean circulation patterns, among other things.

Human-produced changes in atmospheric composition and land use.
Ever since the industrial revolution began, and coal, oil and natural gas usage began in earnest, the products of the burning of these fuels, especially carbon dioxide, began accumulating in our atmosphere at an accelerating rate. This change in the amount of carbon dioxide in the air, from a pre-industrial level of about 280 molecules of CO_2 for every million air molecules (mostly nitrogen and oxygen), to the current level of about 394 ppm ("parts per million") has increased the trapping of the Earth's emitted infrared radiation, reducing that which escapes into space and thus contributing to a positive energy balance. (Refer to Figure 1 in Lesson 1). We will discuss this topic in more detail in Lesson 3 on the "greenhouse effect".

In addition, humans have significantly altered the amount of forest cover and thus reduced the amount of CO_2 intake relative to that prior to the explosion of the human population. The change in the vegetation and other human-induced land use practices also changes the reflectance of the land surface which in turn affects the amount of reflected sunlight. This is discussed in Lesson 6 on the Carbon Cycle.

Human production of tiny airborne particles (“aerosols”)
Although most of us think of "aerosols" as the product of spray cans, the term as used in climate science refers not just to tiny airborne liquid droplets but also to very small solid particles. Some of these are very similar to the sulfate particles described above resulting from volcanic eruptions, but industrial aerosols stay airborne only for a few days to weeks. However, given the huge industrial growth, especially since WW II, the cumulative effect has been very significant. Efforts during the 1970's, 80's and 90's aimed at controlling air pollution in Europe and the U.S. reduced the rate of increase of these emissions. In the developing world however, especially China, where huge amounts of coal are being consumed, but without strong controls on capturing these particulates significant forcing is occurring that is mostly cooling--but not entirely. Some of the particles --especially soot or "black carbon"--have a warming effect, especially by reducing the reflectance of ice and snow. The aerosols also interact with clouds in a way that is not yet well understood. As is now well known, many of these human-produced particulates have a very negative effect on human health and on the environment.

FEEDBACKS

Increase in water vapor as the Earth warms
Water vapor is the most effective molecule in the atmosphere in terms of blocking infrared radiation, but it is not considered a "greenhouse gas" as the term is usually used by Climate Scientists. This is for reasons that will be described in Lesson 3 on the greenhouse effect. It currently accounts for about two to three times the blocking of outgoing infrared radiation compared to the current amount of greenhouse gases. As warming occurs in response to any of the warming forcings, the warmer air holds more water vapor before it condenses and falls as rain or snow. More water vapor in the atmosphere traps more

infrared radiation thus ***enhancing*** the energy imbalance that would occur in the absence of this effect. Thus, this is a ***positive*** feedback process.

<u>Increase in cloudiness with increasing water vapor as the Earth warms.</u>
Increase in cloudiness is also a likely result of increasing water vapor, but the production of clouds, and especially how their formation is influenced by the aerosols describe above, is very complex and not fully understood and is one of the most active areas of forefront climate science research. Additionally, some types of clouds act mostly to reflect sunlight, thus acting to reduce sunlight reaching the Earth, thus producing cooling. But some other types of clouds produce additional infrared trapping, leading to additional heating just as increased atmospheric water vapor does. On balance, current scientific opinion seems to be that the overall effect of the clouds acts as a slightly negative feedback--but when taken together with the increase in heat trapping by the water vapor described in the first feedback process above, the overall effect of the response of water vapor to a forcing is a fairly strongly positive feedback. You can see why climate science at the forefront of research can get complex!

<u>Change in the reflectance of the Earth's surface as melting snow or ice is replaced by darker ocean or land surfaces</u>
This is especially important in the polar regions, where, in response to any of the warming forcings, ice and snow melt and these reflective surfaces are then replaced by the darker ocean or land surfaces. This leads to less reflected sunlight, hence **enhanced** heating, so this is another ***positive*** feedback.
The fraction of the Sun's energy that is reflected back to space is termed the **albedo,** so this feedback is sometimes called the "albedo feedback".

<u>Release of CO_2 into the atmosphere as the ocean's warm.</u>
A good deal of CO_2 is dissolved in the oceans, but just as fizzy carbonated drinks will release CO_2 when heated, when the ocean warms in response to a warming forcing, the ocean will release CO_2, thus trapping more outgoing infrared radiation and enhancing the forcing, so this too is a ***positive*** feedback.

There are many other feedback processes, but these are among the most important and serve to illustrate the concept.

<u>Addendum added December 2012: The Permafrost Carbon Feedback.</u>
Recently, some climate scientists are studying what may become an additional significant positive feedback. At high northern latitudes, especially in northern Siberia, but also in Canada and Alaska, there are vast areas where the ground stays permanently frozen in layers several feet thick. This "permafrost" contains very large amounts of carbon. Due to the rapidly warming arctic regions, large areas of the permafrost are now melting. In the process they release this carbon to the atmosphere, some of it in the form of methane, that, molecule for molecule, is a more potent greenhouse gas than carbon dioxide. This is an active area of research and bears careful monitoring.

Finally, there are some common misconceptions about feedbacks so a few concluding remarks are in order as well as a few caveats:

1) We have illustrated these feedbacks by imagining a warming forcing (for example a slight ***increase*** in solar brightness), and positive feedbacks would ***amplify*** this warming. But if there is a cooling forcing (for example a slight ***decrease*** in solar brightness), the same positive feedback would ***amplify*** this ***cooling***. Thus, ***positive*** feedbacks ***amplify*** forcings no matter whether they are heating or cooling forcings. This may be a confusing concept to some, so let's illustrate it with the snow-and-ice "albedo" feedback described above. We described how the albedo feedback would amplify some warming forcing. But the reverse happens for a cooling forcing (for example the Sun getting a little dimmer.) The slight cooling caused by a dimmer Sun will cause more snow and ice to form. That in turn means that the darker ocean and land surfaces will be replaced by highly reflective snow and ice, meaning less energy received in the Earth's climate system, thus **enhancing** the amount of cooling from the slightly dimmer Sun.

2) ***Negative*** feedbacks, on the other hand, ***oppose*** the forcings, but they do not reverse the direction of the forcing. So, even if the sum of all the feedbacks in the climate system ended up being negative (contrary to what is almost certainly the case in the current climate system), their effect on a warming forcing would be to ***diminish*** the effect of the warming forcing compared to its effect if acting without feedbacks, but ***not to reverse the warming*** and produce overall cooling.

3) Readers may have noticed that CO_2 appears in the list of forcings when produced by human activities, since humans may, or may not, choose to limit the amount of greenhouse gases they produce, but they are not obliged by a law of nature to do so! However in response to other forcings, CO_2 responds as part of a feedback loop. This will be discussed in Lesson 7 on the Ice Ages. Failure to understand this dual role of CO_2 has lead to erroneous statements about whether increased carbon dioxide levels should precede or follow temperature changes during the transitions to and from ice ages.

4) As a practical matter, the formal distinction we have made in defining forcings and feedbacks is unnecessarily rigid under some circumstances. There are very large differences in the rapidity with which various feedbacks respond to various forcings, just as there are huge differences in the time over which various forcings act. Thus, if we are interested in how the climate system responds over a few decades, or a century or two, to the more rapidly applied forcings, rather than how it responds after many thousands of years, then some of the slower acting feedbacks can be considered 'frozen' in time (literally, in the case of the large ice sheets!) while the more rapid feedbacks 'do their thing'.

5) The Earth is of course not one uniform entity and various feedbacks will not respond exactly the same way to different forcings over different parts of the Earth. Nor is the forcing itself from a particular process the same over the entire Earth. In the case of the Ice Ages, discussed in Lesson 7, the forcing associated with the slow subtle changes in the Earth's orbit may be very small when averaged over the entire surface of the Earth, yet be quite large in the polar regions. But they still have profound effects over the entire globe when the relevant feedbacks have had time to take effect.

Items (4) and (5) are closely associated with the concept of 'climate sensitivity' which will be discussed in Lesson 8: "Impacts of Continued Climate Change".

A discussion of forcings and feedbacks can be found in many sources. For a good general introduction to material in this Lesson (and the other Lessons as well see: "Understanding and Responding to Climate Change", 2008 Edition, published by the National Academies Press.
A pdf file of this booklet can be freely obtained and is available through the Resources page of this website.