Handout on Feedbacks

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Introduction

We began our treatment of the climate system with the simple observation that steady temperatures occur when the flux of heat into a system is balanced by an equal flux of heat out of the system. When something disturbs that balance we call the disturbance a **forcing** and we figure out the system's **response** to that forcing. If the forcing causes the heat in to exceed the heat out, then the response is for the system's temperature to rise.

Feebacks occur when the system's response becomes a forcing in its own right. It is easiest to think of this in terms of audio feedback that you hear when the volume on a public address system is turned up too loud or a microphone is placed too close to a loudspeaker. Soft noises (forcings) are picked up by the microphone, amplified, and played back from the speakers (response). If the microphone then picks up the amplified sound from the speakers, the response becomes another forcing, which is amplified, played back even louder, picked up again, amplified more, played back again louder still, and so on until it becomes an annoying or even painful squeal.

This kind of feedback, where the system's response produces a secondary forcing in the same direction as the original forcing, is called **positive feedback**, and it amplifies the effect of the original forcing.

Another kind of feedback is familiar: you have used **negative feedback** any time you engage the cruise control in a car or set a thermostat to control the temperature in your home. In negative feedback, the response of the system creates a secondary forcing in the opposite direction to the original forcing. With cruise control, when you start climbing or descending a hill, gravity acts as a forcing to slow the car down or speed it up; the cruise control responds by adjusting the amount of gasoline going to the engine: a secondary forcing that opposes the original forcing and keeps the car's speed from changing very much.

When the temperature outside a house falls, this forcing causes the temperature inside to fall and the thermostat responds by turning on the furnace: a secondary forcing that opposes the cooling and keeps the indoor temperature fairly constant.

The earth's climate system has many positive and negative feedbacks, and understanding and measuring these is a big challenge for climate science. Most of our uncertainty about how severe global warming will be is due to scientific uncertainty about feedbacks.

The Stefan-Boltzmann Radiative Feedback

It is easiest to discuss feedbacks if we begin with a feedback that most climate scientists take for granted so thoroughly that they don't even think of it as a feedback: If the earth starts out at equilibrium and something—a volcanic eruption, a change in the sun's brightness, or a change in the amount of greenhouse gases—disturbs the balance of heat in and heat out, the temperature will start to rise or fall. As we discussed in the first week of the semester, if nothing changes the imbalance of heat flow then the earth will heat up or cool down forever.

But this doesn't happen: in fact, the earth always comes to a new equilibrium because as the temperature rises or falls, the Stefan-Boltzmann law tells us that the changing temperature (the response to the original forcing) changes the amount of heat going out to space (this is a secondary forcing that acts as a feedback).

If the original forcing heats the earth by making $I_{\text{in}} > I_{\text{out}}$, then the temperature will rise and I_{out} will increase until it equals I_{in}, at which point equilibrium will be restored. The original feedback increased $I_{\text{in}} - I_{\text{out}}$ and the response (rising temperature) decreased $I_{\text{in}} - I_{\text{out}}$, so the Stefan-Boltzmann feedback is **negative**.

Simple Mathematical Treatment

While the details of climate feedbacks can be very complicated, we can use a simple mathematical approach to see how they add up: Scientists often use the letter Q to represent heat flow, so we will call the change in the balance of net heat flow into the earth:

$$Q_{\text{forcing}} = I_{\text{in}} - I_{\text{out}}.$$

If $Q_{\text{forcing}} > 0$ then $I_{\text{in}} > I_{\text{out}}$, so Q_{forcing} will have a heating effect. If $Q_{\text{forcing}} < 0$ then $I_{\text{in}} < I_{\text{out}}$, so Q_{forcing} will have a cooling effect.

We describe the response of the earth system's heat flow to a change in temperature by a **feedback parameter**. When temperature changes by ΔT, it causes Q to change by

$$\Delta Q = f \Delta T \tag{1}$$

If the feedback parameter is positive, then a rise in temperature will produce a positive ΔQ, which will tend to heat the earth even more. If the feedback parameter is negative, then a rise in temperature will produce a negative ΔQ, which will tend to stabilize the temperature by producing a cooling that will diminish the original heating.

The temperature T is measured in Kelvin and the heat flux is measured in W/m^2, so the feedback parameter f is measured in units of Q/T, or Wm^{-2}K^{-1}.

Each feedback has its own parameter f, and we can approximate the total feedback in the earth system as

$$f = f_0 + f_1 + f_2 + \cdots, \tag{2}$$

where $f_0 = -3.2\,\text{Wm}^{-2}\text{K}^{-1}$ is the Stefan-Boltzmann feedback factor and $f_1, f_2, \ldots$ are other feedbacks, such as ice-albedo, water-vapor, etc.

If we apply a forcing Q_{forcing}, it disturbs the equilibrium of the planet. To return to equilibrium, we need to bring Q back to zero by adding an equal and opposite change, $\Delta Q = -Q_{\text{forcing}}$.

We can turn equation 1 around to write

$$\Delta T = \Delta Q / f = -Q_{\text{forcing}} / f, \tag{3}$$

If the only feedback is the Stefan-Boltzmann feedback, f_0, then a forcing of $Q_{\text{forcing}} = +1$ W/m^2 will cause the temperature to rise by

$$\frac{-1\,\text{W/m}^2}{f_0} = \frac{-1\,\text{W/m}^2}{-3.2\,\text{Wm}^{-2}\text{K}^{-1}} = 0.31\,\text{K}$$

Now let's consider what happens when we include the other feedbacks in the earth system:

$$\Delta T = \Delta Q / f = \frac{-Q_{\text{forcing}}}{f_0 + f_1 + f_2 + \cdots} = a \times \frac{-Q_{\text{forcing}}}{f_0}, \tag{4}$$

where $a = f_0 / f$ is called the **amplification**. If the sum of $f_1 + f_2 + \cdots > 0$, then we say that the climate system is dominated by positive feedbacks, the amplification factor will be greater than 1, and the total warming due to Q_{forcing} will be larger than it would for the Stefan-Boltzmann feedback alone.

If the sum of $f_1 + f_2 + \cdots < 0$, then we say that the climate system is dominated by negative feedbacks, the amplification factor will be less than 1, and the total warming due to Q_{forcing} will be smaller than it would if the Stefan-Boltzmann feedback were the only thing.

The table below shows the best estimtes for the major feedbacks in the earth system and our uncertainties about them:

Feedback	Value
Stefan-Boltzmann	-3.2
Water vapor (including lapse-rate)	$+1.2 \pm 0.5$
Cloud	$+0.6 \pm 0.7$
Ice albedo	$+0.3 \pm 0.3$
Total: $f_0 + f_{\text{water vapor}} + f_{\text{cloud}} + f_{\text{ice-alb.}}$	-1.1 ± 0.5

We can calculate the amplification factor:

$$a = \frac{f_0}{f} = \frac{-3.2}{-1.1} = +2.9$$

so the feedbacks in the earth system will produce about three times as much warming as we would get from the Stefan-Boltzmann feedback alone.

Doubling carbon dioxide in the atmosphere would create a radiative forcing of around $3.7\,\mathrm{W/m^2}$, which would produce about $3.4\,\mathrm{K}$ warming.