Summary

Topic 1 covered the way energy flows into and out of the Earth’s climate system and the consequences of an energy imbalance in the Earth’s climate system.

In topic 2 we defined *forcings*: processes external to the climate system that alter the flow of energy into or out of the Earth’s climate system. In this topic, 3, we define and examine *feedbacks*: processes internal to the climate system that either amplify or oppose forcing processes.

An example is the “ice feedback”:
In response to a forcing that causes warming, some ice and snow covered surfaces melt. Ice and snow are highly reflective. Upon melting, they are generally replaced by darker surfaces. Darker surfaces reflect less, and absorb more, sunlight, thus amplifying the initial warming by absorbing more of the Sun’s energy.

Another feedback, and likely the most important one, is the response of water vapor to warming or cooling caused by forcings. In an Appendix to this topic, we examine some of the basic physics involved in the water vapor feedback.

Feedbacks

**What are “feedbacks”?**
In topic 1 we stated the basic law of energy balance, and how it applies to the Earth’s climate system:
- Measure the amount of incoming radiation from the Sun at the top of the atmosphere.
- Subtract the outgoing sunlight directly reflected back into space.
- Also subtract the outgoing infrared heat given off by the Earth that escapes into space.

If these three quantities don’t cancel out, the Earth’s climate system is not in energy balance. Consequently, the Earth’s climate system will heat up or cool off.

In the previous topic, topic 2, we defined and discussed several forcing processes that change the energy balance of the Earth’s climate system.

In this topic, 3, we define and discuss “feedbacks”: how the climate system responds to some external forcing.
Feedbacks are responses to the forcings that either amplify ("positive feedbacks") or oppose ("negative feedbacks") the effects of the forcings.

**Four important feedbacks**

1. **Increase in heat-trapping atmospheric water vapor as the Earth warms**
   As the oceans warm, the amount of water vapor in the atmosphere increases. Water vapor traps heat, (i.e. it is a powerful greenhouse gas) and thus leads to further warming. This in turn leads to still more atmospheric water vapor, and so on. It is thus a positive feedback.

   Further explanation is given below and in the Appendix

2. **An increase in cloudiness with increasing water vapor as the Earth warms.**
   Some kinds of clouds reflect a lot of sunlight, so less sunlight is available to warm the Earth. An increase in this type of cloud in response to increased water vapor is thus a negative feedback.

   But some kinds of clouds have the opposite effect, since, being composed of water, they also trap outgoing infrared radiation. Thus, increased cloudiness in response to increased water vapor can end up as either a negative or a positive feedback, depending upon more specific circumstances.

3. **A change in the reflectance of the Earth’s surface as melting snow or ice is replaced by darker ocean or land surfaces**
   This is especially important in the Polar Regions, where, in response to any of the warming forcings, ice and snow melt. These highly 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.

4. **Release of CO₂ into the atmosphere as the ocean’s warm.**
   A good deal of CO₂ is dissolved in the oceans. But just as fizzy carbonated drinks will release CO₂ when heated, so when the ocean warms in response to a warming forcing, the ocean will release carbon dioxide.

   Since this increased amount of CO₂ traps more outgoing infrared radiation, it enhances the forcing, so this too is a positive feedback. It is a relatively slow feedback and probably played an important role in the transition between ice ages and interglacial periods.

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

**Feedback time scales**

Just as in the discussion of forcings, there are different time scales associated with these feedbacks. The amount of water vapor in the atmosphere responds rather quickly to changes in the ocean temperature, and is thus considered a fast feedback.

At intermediate time spans, sea ice, such as that at the North Pole and the southern ocean surrounding Antarctica responds both seasonally, and over decades. In fact, the feedback
associated with the decline of summer sea ice in the Arctic is a major reason why temperatures are increasing more rapidly in the far north compared to the global average.

On the other hand, the enormous thick ice sheets covering Greenland and Antarctica are so thick and extensive that centuries or millennia are required before a large change in their total area, and thus total reflectance, occurs. This is an example, therefore, of a very slow feedback.

We now examine the water vapor feedback in a bit more detail.

**The water vapor feedback**

Water vapor is the most effective molecule in the atmosphere in terms of blocking infrared radiation. However, it is not considered a "greenhouse gas" as the term is usually used by climate scientists. The reason for this will be explained in topic 5 dealing with greenhouse gases.

The amount of water vapor in the atmosphere varies substantially over portions of the globe, especially between the polar and equatorial regions. But on average, it accounts for about two or two and a half times as much blocking of outgoing infrared radiation as all other gases that absorb infrared radiation.

As warming occurs in response to any warming forcing, the warmer air is capable of containing 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 feedback. Thus, this is a positive feedback process.

The amount of water vapor that can exist in the atmosphere before it condenses back to the liquid phase and falls as rain or snow increases sharply with temperature. See the Appendix for a simple discussion of why this is so.

A frequently encountered myth is that since water vapor traps more heat than carbon dioxide, we really shouldn't be worrying about putting more carbon dioxide into the atmosphere. Here is a wonderful five-minute video that explains the fallacy in this myth: https://www.youtube.com/watch?v=u9L49p9Y8Mg&feature=youtu.be

This video is taken from an online course that features many other excellent explanations of basic climate science facts and myths surrounding them. Two other such videos are referred to below and others will be mentioned throughout these tutorial topics.

What role do clouds play in the water-vapor feedback?

An increase in cloudiness is also a likely result of increasing water vapor. The details of the production of clouds of various types are not fully understood. How their formation is influenced by both natural and man-made very small particles (called “aerosols”) is very complex.

In fact, the details of cloud formation and how clouds influence the energy balance of the Earth’s climate system is one of the most active areas of climate science research. Some types of clouds act mostly to reflect sunlight, thus acting to reduce sunlight reaching the
Earth. But other types of clouds produce additional infrared trapping, leading to additional heating, just as increased atmospheric water vapor does.

On balance, prevailing opinion seems to be that the overall effect of clouds is to cool, but clouds may act as a positive feedback as further warming occurs. Here is another nice video discussing the situation. But again it needs to be emphasized that this is still an active area of research and the conclusions are not firm: https://www.youtube.com/watch?v=TW33e9J3fRc

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

**Some additional remarks about feedbacks**

1) **Positive feedbacks don’t imply something “good”**
   Notice that when describing feedbacks, the use of the terms “positive” or “negative” do not imply “good” or “bad” reactions, 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. This is because they enhance the effects of any increase in energy input from increased levels of human-caused CO₂, currently the dominant forcing.

2) **About positive feedbacks**
   Positive feedbacks amplify both warming and cooling forcings. 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 were 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.

3) **About negative feedbacks**
   Negative feedbacks, on the other hand, oppose the forcings, but they do not reverse the direction of the forcing. So, even if the net result 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. But they would not reverse the warming.

4) **Is Carbon Dioxide a forcing or a feedback?**
   Readers may have noticed that CO₂ appears as an agent in the forcings list 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, CO₂ responds as part of a feedback loop. This will be discussed in topic 9, in connection with on the Ice Ages. Failure to understand this dual role of CO₂ has led to erroneous statements about whether increased carbon dioxide levels should precede or follow temperature changes during the transitions to and from the ice ages.

5) **The distinction between forcings and feedbacks is not a rigid one**
As a practical matter, the formal distinction we have made in defining forcings and feedbacks is unnecessarily rigid under some circumstances. As discussed above concerning feedback time-scales, there are very large differences in the rapidity with which various feedbacks respond to various forcings. Similarly, there are huge differences in the time over which various forcings act, as emphasized in topic 2.

Suppose we are interested in how the climate system responds over a few decades to the more rapidly acting forcings, rather than how it responds after many thousands of years. In that case, some of the slower acting feedbacks can be considered 'frozen' in time. (This is literally true, in the case of the large ice sheets!)

![Figure 1. During the last ice age, when the average global temperature was only 6 degrees C cooler than today, much of the northern hemisphere was covered in thick ice. As the climate became warmer (driven by the Earth’s orbital change forcing, discussed in topic 7), the ice retreated, diminishing the amount of sunlight and thus acting as a very slow feedback. (This illustration taken from a course taught by Dr. Chris Castro, University of Arizona.)](image)

APPENDIX

**Why the amount of atmospheric water vapor is temperature-sensitive, and the concept of “latent heat”**

Appendix Summary

The gaseous phase of H$_2$O, (water vapor), is in equilibrium with liquid water when molecules leave the liquid phase at the same rate as they return to it.
The reason why the amount of water vapor in the atmosphere is very sensitive to temperature is discussed. Only a small fraction of H₂O molecules in liquid water have enough energy to overcome the attractive forces of their neighbors and escape into the air. This fraction quickly grows with increasing temperature.

The concept of “latent heat” is discussed. Energy is required to evaporate water, but when water vapor condenses back into liquid form, it releases this energy as heat. Thus, rising columns of moist air can be considered to be transporting energy in the form of latent heat. This is released as actual heat when the water vapor condenses into droplets.

**The three phases in which the H₂O molecule can exist**
The water molecule, H₂O, occurs in three different phases:
- As ice, with the molecules locked together in a lattice.
- As liquid water, where the molecules can move, but where there are still significant forces between the individual H₂O molecules.
- As gaseous water vapor, where the water molecules move freely, simply bouncing off other molecules in the atmosphere, (usually N₂ and O₂ molecules, since these are the most abundant.)

We will consider in this appendix the exchange of H₂O molecules primarily between the liquid and gaseous phases.

**The equilibrium between liquid water and water vapor.**
Imagine a jar of perfectly dry air, in which a pan of water is quickly slipped inside it. Suppose further that both are at the same temperature. What happens?

Water molecules will leave the pan of water and enter the air. Eventually, equilibrium will be reached. This occurs when the number of water vapor molecules in the air has grown to the point where the rate at which the number of water molecules returning to the pan of water is the same as the rate of those leaving it.
What determines how many H₂O molecules will be in the gaseous phase in equilibrium? Why is this number quite temperature-sensitive?

For the molecules in the vapor phase, almost all of them striking the surface will be captured by the liquid. The rate at which the water vapor molecules strike the surface is determined by the number of water vapor molecules per cubic centimeter times their average velocity. This velocity is only weakly dependent on the temperature, increasing as the square root of the temperature.

But the situation is different for the rate at which molecules in the liquid phase escape. This depends as well on the density of water molecules in the liquid, but this is pretty much fixed, since water is hardly compressible.

In order for a water molecule to escape into the air, it must have some minimum energy. This is needed to overcome the attractive forces between it and its neighbors, as shown in Figure A-2.
Figure A-2. A schematic illustration of the electrical attractive forces ("bonds") between the oxygen atom in one molecule of water and the hydrogen atoms in adjacent molecules. These attractive forces give rise to the phenomenon of surface tension and require that a molecule have considerable energy to escape from the liquid.

The fraction of water molecules in the liquid having this minimum energy is relatively small at normal temperatures.

Furthermore, as we now explain, this fraction of molecules able to escape depends strongly on the temperature of the water.

**What is the distribution of speeds (or kinetic energy) of the water molecules?**

The molecules in a liquid or gas do not all have the same speed but have a *probability distribution* known as the Maxwell-Boltzmann distribution.

Since the energy of motion (kinetic energy) of a molecule is related to the square of its velocity (\( E = \frac{1}{2}mv^2 \), where \( m \) is the mass of the molecule) this curve can also be plotted in terms of the probability that a molecule will have a given kinetic energy. The shape of this probability distribution depends upon the temperature, as shown in Figure A-3.
**Figure A-3. The probability that a molecule will have a certain kinetic energy for three different temperatures.**

Suppose the red line in figure A-3 represents the minimum energy a water molecule must have to break free of the surrounding molecular attractive forces and leave the liquid.

The temperature-sensitivity of the fraction able to escape arises because at typical temperatures characterizing liquid water on Earth, (say between 0°C and 25°C) the fraction of molecules having this minimum energy changes dramatically.

This is illustrated schematically in the figure by the area of the *blue* shaded area for 0°C and by the much larger (*blue + green*) area for 25°C.

This means that for equilibrium to be established as the temperature increases, there must be a lot more molecules in the gaseous phase to balance the increasing number of escaping molecules from the liquid.

**The concept of vapor pressure**

Instead of speaking of the density of molecules in the gaseous phase in equilibrium with the liquid at some temperature, it is customary to speak of the “vapor pressure” or “partial pressure” of H₂O. The word “partial” here refers to the pressure exerted only by the H₂O molecules, not the more abundant nitrogen and oxygen air molecules.

The ideal gas law applies relating the density of water vapor molecules to the pressure these molecules exert at a given temperature (see the Appendix in topic 1.)

*Vapor pressure* thus refers to the gas pressure exerted by just the water vapor molecules when in equilibrium with the liquid at any given temperature.

Here is a graph of the vapor pressure for H₂O as it changes with temperature.
Figure A-4. The vapor pressure of H$_2$O as a function of the temperature. The units of pressure are “millibars”. The pressure of the entire atmosphere at sea level is about 1000 millibars. Note that the pressure scale is logarithmic, so from 0.1 to 1 is the same distance on the vertical axis as 1 to 10 and 10 to 100.

Along the black curve there is equilibrium between the liquid and gas phase. Below this curve, evaporation takes place; above it, condensation will occur.

Similarly for the red curve, which is the vapor pressure above ice. Below the red curve, ice sublimes, which means it goes directly from the solid to the gaseous state. Above the red line, ice crystals form. (Dry ice is frozen CO$_2$; it sublimes and doesn’t exist as a liquid.) See the text for the green line.

The change of the vapor pressure of water with temperature at normal Earth temperatures.
At the current average temperature of the Earth (about 15 °C) just a one degree centigrade increase results in an increase of the vapor pressure of about 7 percent. Averaged over the Earth, the actual pressure of water vapor is about 70 percent of the equilibrium vapor pressure. The ratio of the actual pressure to the equilibrium vapor pressure is called the relative humidity—i.e., the average relative humidity is about 70 percent. It is much higher in the steamy tropics and lower in the deserts.

Why astronomers put telescopes at the South Pole
Note the extremely low vapor pressure above ice at very cold temperatures in the red line of figure A-4. At the high altitudes and extremely cold temperatures of inner Antarctica, this often results in nearly all the atmospheric water vapor being “frozen out”. As noted in this topic and discussed further in topic 5, water vapor strongly absorbs infrared radiation.
This is frustrating to astronomers who want to be able to detect such radiation from celestial objects. So, in spite of the extreme conditions, they have located telescopes near the South Pole to take advantage of the extremely low amounts of water vapor in the atmosphere above them.

**Evaporative cooling and latent heat**

One consequence of the discussion above is that since only molecules considerably faster than the average can escape from the surface, the *average* energy of the *remaining* molecules at the surface ---and hence their temperature, is reduced.

(If you have a room full of 100 people and take their average height, but then ask the ten tallest people to leave, the average height of those remaining will decrease.)

Thus, during evaporation, the surface layer will cool, as will the air molecules adjacent to the surface. This is how evaporative coolers work.

An important concept related to this discussion is that of *latent heat*. When \( \text{H}_2\text{O} \) molecules in the gaseous phase return to their comrades in the liquid phase, they are welcomed with enthusiasm and give back to them the energy that was needed to escape, reversing the energy exchange. This release of heat is called the *heat of condensation*.

One can think of evaporated water molecules as carrying the potential for returning the energy used in their evaporation when they condense, and this “latent heat” plays an important role in the energy exchange of the various components of the climate system. In fact, the release of latent heat is a major energy source for hurricanes and thunderstorms.

**Cloud formation**

Imagine a warm summer day with a temperature near the surface of 30 °C (= 86 °F.) Further imagine a blob of air warmed by the ground to that temperature, with moisture content equivalent to 50 percent relative humidity. Warmed by the ground, this blob buoyantly rises, and as it rises, the surrounding pressure drops and so the blob expands and cools. This means the water vapor partial pressure within the blob also drops.

The green line in Figure A-4 tracks the partial pressure of the water vapor during this process. At about 10 °C the green line of Figure A-4 intersects the black equilibrium vapor pressure curve. At this point, liquid water can exist in equilibrium with the water vapor.

But this doesn’t mean condensation will spontaneously occur. Random chance encounters between two \( \text{H}_2\text{O} \) molecules in the gaseous phase aren’t sufficient to lead to the formation of water droplets. Instead, water vapor molecules need a congenial meeting place where condensation can occur. Very small particles, either man-made or natural (for example, tiny salt particles wafted up from the ocean to high altitudes), serve as the nuclei for condensation of water droplets. When the droplets have grown sufficiently, they fall as rain.