Chapter 7: Energy Balance of the Earth

Part I. The Basic Concept of Climate: Radiative Energy Balance

The temperature of the earth’s surface has been remarkably constant over geologic time. Even the dramatic cooling during the ice age represented a change of only 3°C in the global average surface temperature, occurring over thousands of years. Seasonal changes in temperature, although large in a particular place, correspond to very tiny changes in global mean temperature. This chapter examines how the temperature of the earth is maintained nearly constant while it receives vast amounts of energy from the sun, with large variations in time and space.

The only way for the earth to gain or lose energy is by absorption and emission electromagnetic radiation. Only a very tiny amount of energy is associated with the flows of mass in outer space, such as the stream of particles that emanate from the sun (the solar wind). Conduction of heat requires the presence of molecules that can carry energy in translation, vibration or rotation, but outer space is essentially devoid of matter. The interplanetary medium contains insufficient material to transport exchange energy by these processes, leaving radiant energy as the only process capable of moving significant amounts of energy.

Evidently, to maintain the long-term stability of earth’s temperature, the planet must radiate to space a flux of energy sufficient to just balance the input from the sun, i.e. the earth is, to good approximation, in radiative energy balance. Using concepts that we have already studied, we can determine quantitatively how this energy balance works, including the influence of the earth’s reflectivity, distance from the sun, etc.

Consider an imaginary sphere centered on the sun, with radius \( r = 1.5 \times 10^{11} \text{ m} \), the radius of earth’s orbit (see Figure 7.1). The surface area of this sphere is \( 4\pi r^2 \).

![Figure 7.1. Diagram of the sun and earth, and an imaginary sphere with radius 1.5x10^{11}m with the sun at the center.](image)

We can compute, using the Stefan-Boltzmann Law, the total amount of energy (L) radiated by the sun each second,

\[
L = \sigma T_s^4 \times 4\pi R_s^2 = 3.9 \times 10^{26} \text{ watts},
\]

where \( 4\pi R_s^2 \) is the surface area of the sun \((R_s=6.6 \times 10^8 \text{ m})\), \( \sigma T_s^4 \) is the Stefan-Boltzmann law, and \( T_s \) is the temperature of the sun’s surface, 5800 K.
Since there is negligible matter in the interplanetary medium to absorb and store the sun’s energy, the same total amount of energy $L$ must also cross the sphere of radius $r$ each second. The solar flux (Watts m$^{-2}$) at earth’s orbit, $F_s$, defined as the energy crossing a square meter of the sphere at earths orbit each second, is given by

$$F_s = \frac{L}{4\pi r^2} = \frac{\sigma T_s^4}{4\pi (1.5\times10^{11})^2} = 1379 \text{ W/m}^2$$

The quantity $F_s$ (also called the solar constant) is the radiant energy from the sun that falls per second a 1 m$^2$ surface oriented perpendicular to the sun’s rays, at the top of the earth’s atmosphere.

The total solar energy striking by the earth per second can be calculated by multiplying $F_s$ by the shadow area (not the total surface area!) of the earth, i.e. the area of solar beam intersected the earth (see Figure 7.2).

**Figure 7.2.** The amount of energy striking the earth is given by the shadow area (black circle) \times the solar flux, \(\pi R_e^2 F_s\). (\(R_e\) is the radius of the earth).

The total energy flux striking the surface of the earth is therefore $F_s \pi R_e^2$.

Not all solar radiation intercepted by the earth is absorbed. The fraction of incident solar radiation reflected is defined as the albedo, $A$, and the fraction absorbed is therefore $(1-A)$. The total energy input to earth per second is thus

$$E_{\text{abs}} = F_s \pi R_e^2 (1 - A).$$

The earth’s albedo was first measured by observing earthshine on the moon, reflected back to earth and visible just after the new moon. It is now measured from spacecraft. About 33% of the solar energy incident on the earth is reflected back to space, $A=0.33$. The albedo of the earth’s surface is in general much lower than 0.33, about 0.07 for land with vegetation, 0.05-0.1 for the ocean, with somewhat higher values for deserts (~0.2) and snow and ice (0.6 – 0.9). Most of the reflection of solar radiation from earth is due to clouds, with notable contributions from sea ice and glacial ice in Antarctica and Greenland. Thus the albedo, and the entire energy budget of the planet, is sensitive to cloudiness and ice cover, factors that change over both short time scales (weather) and long time scales (climate).
Now let us compute the energy output of the earth. Consider an idealized planet at earth's orbit, with the same albedo, but with no atmosphere. We will take into account the effect of the atmosphere shortly. The planet rotates quickly and is an efficient conductor of heat, so the input is absorbed on all sides and the whole planet reaches a single temperature. Let us further assume that this idealized planet is neither heating up nor cooling off, so the amount that it radiates to space each second equals the amount absorbed (input). What temperature will this body have?

Once again the Stefan-Boltzmann Law applies. The total energy emitted per unit area is given by $\sigma T^4$, and the emitting area is $4\pi R_e^2$. The total energy emitted by the planet per second is therefore

$$E_{\text{emit}} = 4\pi R_e^2 \sigma T^4.$$

Energy balance requires that input=output, when averaged over a long-enough period of time, i.e. on average $E_{\text{emit}} = E_{\text{abs}}$. Thus

$$4\pi R_e^2 \sigma T^4 = F_s \pi R_e^2 (1 - A) .$$

(This is the Energy Balance Equation). This equation can be solved for the average temperature at which the earth must emit radiation to bring the energy budget into balance, called the effective temperature $T_{\text{eff}}$ of the planet:

$$T_{\text{eff}} = \left[ \frac{F_s (1 - A)}{4 \sigma} \right]^{1/4} = 252.6 \text{ K}.$$ 

The effective temperature of the earth is a basic quantity determined by the balance between solar radiation absorbed and terrestrial radiation (the heat emitted by earth to space, with much longer wavelengths than solar light). It is the temperature of the earth that you would infer by looking from space and measuring the total heat output. The peak of the blackbody curve for terrestrial radiation is about 15 $\mu$m, with most energy emitted between 10 and 30 $\mu$m, wavelengths not visible to the eye.

Note that $T_{\text{eff}}$ is much colder than the surface temperature of the earth. Thus if there were no atmosphere the earth would be too cold for liquid water to exist and there would be no life on the planet. We will now discuss how absorption and re-emission of terrestrial radiation by molecules in the atmosphere raises the surface temperature, the so-called greenhouse effect.

Note: We could also write the energy balance equation, or the effective temperature, directly in terms of basic quantities of the solar system,

$$T_{\text{eff}} = T_s^4 \sqrt[4]{\frac{1 - A}{4}} \sqrt{\frac{R_s}{r}}.$$ 

We see that the temperature of our model planet, with no atmosphere, depends only on the temperature of the sun, the square root of the ratio of sun's radius to radius of earth's orbit, and the fourth root of (1 - Albedo), a weak dependence. We believe that life can exist only in a narrow temperature range, where liquid water can exist, and this equation thus gives basic guidance about planetary systems that might provide suitable environments, i.e. where $T_s \sqrt{R_s/r} = 400 K$ to give $T_{\text{eff}} \sim 275 K$. 

The Greenhouse Effect

In the discussion of Planck’s Law (Section 6.3), we noted that a molecule can absorb a photon only converting the energy of the light into internal energy of the molecule. Absorption of ultraviolet (UV) photons (high-energy) can make electrons jump to a higher-energy shell, which may result in breaking the chemical bonds in the molecule (a process called photolysis). Absorption of the low-energy, infrared photons (terrestrial radiation or heat) can’t break molecular bonds, but can make molecules vibrate or rotate faster. Absorption of infrared radiation is allowed only if the molecule has an asymmetric distribution of charge, e.g. a dipole like the water molecule pictured in Figure 6.2 that feels an electrostatic force from the oscillating electric field of the wave. The CO$_2$ molecule can also absorb infrared radiation, because there is always a certain amount of bending (flexing) of the molecule, and the bent molecule does have a dipole moment even though the linear shape does not.

The most abundant gases in the atmosphere, N$_2$, O$_2$, and Ar, do not have dipole moments, they cannot be bent. Therefore they cannot interact with infrared radiation and neither absorb nor emit terrestrial radiation. They also neither absorb or emit most wavelengths of solar radiation (ultraviolet light is an exception, to be discussed in a later chapter). The relatively rare molecules that can absorb long-wave (terrestrial) infrared radiation are called *greenhouse gases*, because they can trap infrared radiation emitted by the Earth much as the glass in a greenhouse traps heat. The most important greenhouse gases in the atmosphere are H$_2$O and CO$_2$, and gases such as methane (CH$_4$) and chlorofluorocarbons are also significant. The major atmospheric gases, N$_2$, O$_2$, are not greenhouse gases.

Now let’s add an atmosphere to the planet, put in some greenhouse gases, and repeat the energy balance calculation in the previous section. The atmosphere is fairly transparent to solar radiation. The albedo of the earth is about 0.33, thus 2/3 of the solar radiation is absorbed by the surface and then radiated away as heat (at the long IR wavelengths). In the calculation of $T_{\text{eff}}$ we assumed that this radiation went directly to space, but with an atmosphere containing greenhouse gases, some of the terrestrial radiation will be absorbed, heating the atmosphere. We know that molecules that can absorb radiation of a particular wavelength can also emit that radiation according to Planck’s radiation law, thus the atmosphere warmed by absorption of terrestrial radiation will radiate, both to space and back towards the earth’s surface. This *back-radiation* warms the earth's surface.

Thus the atmosphere acts as a blanket, allowing solar energy to reach the surface but preventing the heat from escaping directly back to space. In the following example, we consider a simple planet that resembles the earth (same albedo and orbit), and has a very simple type of greenhouse atmosphere. The atmosphere acts like a mylar blanket (the "space blanket" you can buy in camping stores), allowing solar radiation to pass through, but absorbing all terrestrial (longwave) radiation. We now calculate the surface temperature, and the atmospheric temperature, of this planet.
The atmosphere and the ground radiate energy according to the Stefan-Boltzmann law:

Examine the energy balance of the layer at H (intended to be a scale height, or ~ 7km, on earth) in this hypothetical planet. The total amount of energy radiated per square meter per second is \(2\sigma T_1^4\), \((\text{OUT})\) because the layer radiates equally both up and down. But the amount received by the layer is \(\sigma T_g^4\), \((\text{IN})\) (heated only from below!). If the layer has a balanced energy budget, these two fluxes must be equal \((\text{IN} = \text{OUT})\),

\[
\sigma T_g^4 = 2\sigma T_1^4.
\]

Thus the ground is warmer than the atmosphere by \(T_g = 2^{1/4}T_{\text{eff}}\). This happens because the atmosphere is warmed only by absorbing radiation from the earth's surface, i.e. from one side (below), but it radiates both up and down. The atmosphere must have a lower temperature than the ground in order to satisfy its energy balance.

Of course, the whole planet must still have a balanced energy budget, and energy is emitted back to space by the atmosphere, not by the ground. Thus the amount of energy emitted to space from the atmosphere must equal the amount absorbed by the ground, which means that the temperature of the atmosphere \(T_1\) must be the effective temperature, \(T_{\text{eff}} = [(1 - A)F_s/(4\sigma)]^{1/4}\). The fact that the ground is warmer than the atmosphere may be attributed to the extra input of heat that is received from above, or it may be recognized as a consequence of basic energy balances and simple geometry. These points of view are equivalent.

The greenhouse effect is evidently a natural phenomenon, and a very important one indeed. We know from the earlier lecture that \(T_{\text{eff}} = 253\ K\). For our simple model earth, we compute \(T_g = 253\times 1.18 = 301\ K\). The effective temperature of the earth, 253 K, is too cold (-20 C) for life as we know it. The ground temperature is about 288 K on average over the globe (13 C, slightly cooler than our fictional protoplanet), is just right, neither too hot nor too cold for liquid water to exist and for enzymes to work. "Greenhouse" warming is essential for life on earth.
Climate warming and feedback: an ultra-simple model

How does increasing the amount of infrared absorber in the atmosphere affect climate?

We can develop an equation relating the ground temperature \( T_g \) to the effective temperature \( T_e \), using the layer model extended to \( n \) layers, obtaining

\[ T_g = (n+1)^{2.5} \times T_e \]

We know that \( T_e = 253K \) is fixed by the requirement for energy balance with solar input, unless the albedo changes.

In fact \( n \) may be considered a continuous variable, since we can construct a physical argument about how the radiation balance changes when we move up a small amount in an absorbing atmosphere. Now consider a change of 0.07 layer (7\%) from our mean 1-layer absorbing atmosphere.

\[ (1 + 1)^{2.5} T_e = 1.18 \times T_e = 1.189 \times 253 = 300.8 \]

\[ (1.07 + 1)^{2.5} T_e = 1.20 \times T_e = 1.204 \times 253 = 303.5 \]

This is about what climate models predict for doubling of \( \text{CO}_2 \) in the atmosphere, including some feedback involving increasing water vapor with increasing temperature. Our simple "layer" model gives a global mean temperature rise of about 2.7\(^\circ\) C for this doubling. This may not seem like much, but it is about the same size as the temperature change that took place at the end of the last ice age.

Feedback: Positive (amplification) and Negative (damping) feedback in climate change.

When \( \text{CO}_2 \) is added to the atmosphere, it has only a small effect on the energy balance near the ground. For example, doubling \( \text{CO}_2 \) is equivalent to increasing the heat input to the surface by only about 4 W m\(^{-2}\), about 1\% of the average input of solar energy over the whole planet. Much of the climate warming predicted to result from adding \( \text{CO}_2 \) from fossil fuels is in fact due to positive feedback (amplification): amplification several-fold by increased humidity.

Feedback involving water vapor arises due to warming of the oceans, initially due to extra long-wave radiation from \( \text{CO}_2 \) (the 4 W m\(^{-2}\)), and the relationship between water vapor pressure and temperature. From the water vapor-temperature curve, we see that the vapor pressure of water increases by 10 - 15\% for a temperature change of 3 K. Most of the change in infrared absorption in a climate warming model is due to higher content of water vapor in the atmosphere. The interaction between water vapor and temperature is what is meant by positive feedback in the climate system.

warmer \( \Rightarrow \) more water vapor \( \Rightarrow \) warmer ....

(and vice versa).
The role of positive feedback represents one of the great obstacles to quantitative assessment of future climate warming. The details of distributions of water vapor and clouds are extremely complex and no model really does an adequate job.

The following table summarizes some of the many feedback mechanisms that affect climate in the atmosphere. The ambiguous role of clouds, and the complex relationship between cloudiness and water vapor content of the atmosphere, represent a critical problem for climate models. Climate models do a rather poor job of representing clouds, in part because we don't have a good basic understanding of how cloudiness interacts with surface temperatures.

### Climate Feedback Mechanisms

<table>
<thead>
<tr>
<th>sign</th>
<th>interacting factors</th>
<th>mechanism (response to increase in temperature)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>water vapor</td>
<td>warmer $T$ → vapor pressure increases exponentially $\rightarrow$ more trapping of terrestrial radiation $\rightarrow$ warmer $T$</td>
</tr>
<tr>
<td>+</td>
<td>snow-albedo</td>
<td>warmer $T$ $\rightarrow$ less seasonal snow cover $\rightarrow$ albedo decreases + [other snow effects] $\rightarrow$ warmer $T$</td>
</tr>
<tr>
<td>+</td>
<td>ice-albedo</td>
<td>warmer $T$ $\rightarrow$ melts ice caps $\rightarrow$ albedo decreases $\rightarrow$ warmer $T$</td>
</tr>
<tr>
<td>-</td>
<td>cloud-albedo</td>
<td>warmer $T$ $\rightarrow$ more water vapor $\rightarrow$ greater occurrence of clouds $\rightarrow$ higher albedo $\rightarrow$ cooler $T$</td>
</tr>
<tr>
<td>+</td>
<td>cloud-longwave</td>
<td>warmer $T$ $\rightarrow$ more water vapor $\rightarrow$ greater occurrence of clouds $\rightarrow$ more trapping of terrestrial radiation $\rightarrow$ warmer $T$</td>
</tr>
<tr>
<td>+</td>
<td>CO$_2$-soil carbon</td>
<td>warmer $T$ $\rightarrow$ thawing of frozen peat $\rightarrow$ oxidize organic matter $\rightarrow$ more CO$_2$ in the atmosphere $[\rightarrow$ warmer $T]$</td>
</tr>
<tr>
<td>-</td>
<td>CO$_2$-plant growth</td>
<td>higher CO$_2$ $\rightarrow$ plants grow faster, larger $\rightarrow$ create organic matter $\rightarrow$ less CO$_2$ in the atmosphere $[\rightarrow$ cooler $T]$</td>
</tr>
<tr>
<td>+</td>
<td>$T$-land cover</td>
<td>warmer $T$ $\rightarrow$ forests convert to grasslands $\rightarrow$ lower albedo $\rightarrow$ less evapotranspiration $\rightarrow$ warmer $T$</td>
</tr>
</tbody>
</table>

**Direct and indirect human influences**

<table>
<thead>
<tr>
<th>sign</th>
<th>interacting factors</th>
<th>mechanism (response to increase in temperature)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+/-</td>
<td>land use</td>
<td>albedo, evaporation</td>
</tr>
<tr>
<td>+/-</td>
<td>water pollution</td>
<td>albedo, uptake of CO$_2$ by aquatic plants</td>
</tr>
<tr>
<td>+/-</td>
<td>air pollution (N, S emissions)</td>
<td>albedo, uptake of CO$_2$ by terrestrial plants</td>
</tr>
</tbody>
</table>

Models used to compute response of the climate to increasing greenhouse gases and other perturbations agree well for the cases CO$_2$ only and CO$_2$ plus feedback from water vapor (1.9C), and but predictions show a large spread once the clouds and ice-albedo are added, as shown by the following table from the Intergovernmental Panel on Climate Change (IPCC).

<table>
<thead>
<tr>
<th>Atmospheric change</th>
<th>Change in global $T$ (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double CO$_2$</td>
<td>+1.2</td>
</tr>
<tr>
<td>Double CO$_2$ + water vapor feedback</td>
<td>+1.9</td>
</tr>
<tr>
<td>Double CO$_2$ + water vapor feedback + clouds + ice-albedo feedback</td>
<td>+1.5 - 4.5 (median 2.5)</td>
</tr>
</tbody>
</table>
In addition to feedbacks, human activities have changed atmospheric content of quite a few other gases and of aerosols, and possibly of clouds, which can have the effect of adding to, or counteracting, the influence of CO$_2$ and water. Here is a table summarizing these effects, from the IPCC. Many of these changes are very difficult to model, and this table does not even attempt to put the effects in terms of temperature changes; instead, estimate changes in longwave flux from the atmosphere back to ground are given.

<table>
<thead>
<tr>
<th>Atmospheric change</th>
<th>change in longwave flux (W/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double CO$_2$</td>
<td>1.5</td>
</tr>
<tr>
<td>Increasing CH$_4$, N$_2$O, CFCs</td>
<td>1</td>
</tr>
<tr>
<td>Increase in tropospheric ozone</td>
<td>0.5</td>
</tr>
<tr>
<td>Increase Sulfate Aerosols</td>
<td>$\sim$ -1</td>
</tr>
</tbody>
</table>

Which molecules act like a "blanket" in the infrared?

Light is an electromagnetic wave that interacts with matter by exerting force on the charged particles (electrons, protons) that make up atoms and molecules. The most important force for most applications is the interaction between the oscillating electric field in the light wave and the electric dipole of the atom or molecule. A dipole is basically a distribution of charge that looks like this:

```
+ ...... -
```

Light in the ultraviolet part of the spectrum has sufficient energy in each photon to disturb the distribution of charge around an atom or molecule, creating transient dipoles. Photons emitted by the earth (terrestrial radiation, T= 200 - 300 K, wavelengths longer than about 9 microns) do not have sufficient energy to break a chemical bond or to disturb the electrons in an atom or molecule in the atmosphere. Infrared radiation therefore interacts with molecules that already have a dipole ("dipole moment"), or that can produce a transient dipole by simple bending or stretching.

Terrestrial radiation (longwave infrared light) can only be absorbed by molecules that either have a permanent dipole or that produce a transient dipole by simple bending or stretching.

Most of the atoms and molecules in the atmosphere do not have permanent dipoles and cannot produce a transient dipole by simple bending or stretching: nitrogen and oxygen contain only two identical atoms. The molecules remain perfectly symmetric even if energy is put into vibration, so it is not possible for one atom to be charge + relative to the other -.

**Water** is a bent triatomic molecule (see the picture below), which has a permanent dipole moment. It also readily excited into vibrational motions that induce transient dipoles. Both the permanent and the transient dipoles can interact with the oscillating electric field of a light wave in the infrared part of the spectrum. Water is by far the most abundant of
the atmospheric gases (.1 - 3 %) that have infrared spectra, and it has the richest infrared spectrum. Therefore water vapor is by far the most effective "greenhouse gas". (The small "delta" denotes a fraction of an electron charge; the arrows (right panel) denote motions of the atoms.)

\[ \text{Water} \]
\[ \text{(permanent dipole)} \]

\[ \text{Ozone}\] is also a bent triatomic molecule, but it is much less abundant than water, and mostly is found in the stratosphere, so it has a much smaller role as an infrared absorber. \[\text{Carbon dioxide}\] does not have a permanent dipole, but it is readily excited in a bending mode and is relatively abundant (0.035%). It plays a role second to water as an infrared absorber.

\[\text{Clouds}\] are very much like blankets, absorbing and emitting over almost the entire infrared spectrum. Clouds can be important elements of the greenhouse effect, with strongest influence at night due to their trapping of infrared radiation. This is the reason why cloudy nights are usually warmer than clear nights. Clouds play a dual role in the day, warming the surface by trapping infrared radiation, but cooling the surface by reflecting sunlight; the net effect is close to zero.
Summary of major points in Part I, Energy Balance in the Atmosphere

1. The atmosphere is mostly transparent to solar radiation, and most of the solar energy absorbed by the earth is absorbed at the ground.

2. The earth radiates energy back to space at the same rate that it absorbs energy from the sun. Viewed from space, the earth is *approximately* a black body with an emission temperature of 253K.

3. The atmosphere absorbs some of the radiation emitted by the earth, due to the presence of H$_2$O, CO$_2$, and other trace gasses that have spectral features in the infrared part of the spectrum. The atmosphere re-radiates this radiation both up and down, to space and back to the ground, and this back-radiation warms the surface (the greenhouse effect).

4. Water vapor is the most important gas absorbing infrared radiation in the earth’s atmosphere; carbon dioxide is the second most important, with effects *much* smaller than water vapor. Clouds play a critical role that has proven extremely difficult to represent in climate models.

4. The greenhouse effect is a natural phenomenon. If there were no greenhouse effect, the earth would be too cold for life.

5. There is concern that human activity could cause climate change because human activity has increased the concentrations of carbon dioxide and other gasses in the atmosphere. The concern about global warming is based on fundamental physics, however, it is difficult to predict how much warming there might be, or even to decide if warming due to human activities has already taken place. Even if we knew what the warming would be, it would be very difficult to predict the effects (positive or negative) on human beings, national economies, or ecosystems.

Demonstrations help to visualize energy balance

1. **Black body spectrum.** We examined emission of black body radiation from a carbon arc lamp, and showed that most of the energy is in the red and infrared (invisible to the eye, but detected by the radiometer). Infrared radiation can be sensed by the skin (as heat) but not by the eye.

2. **Greenhouse effect.** We put identical heaters in two beakers, one clear glass and one with black-painted foil or Mylar plastic inside. The foil absorbed the infrared radiation from the heater and re-radiated it, half going back inside the beaker and half outside. As a result, the temperature in the lined beaker became higher than in the clear one. This experiment illustrates the effect of introducing an infrared absorber between a heat source (the heater; the earth) and a cold environment (the room; outer space).
Part 2. Climate Change: Basic physical concepts, issues and concerns
Absorption of infrared radiation by greenhouse gases and clouds

Let us compare the atmospheres of Venus, Earth, and Mars.

- Effective Temperatures
The effective temperatures of these planets depend on their distances from the sun and on their albedos. Note the anomaly that Te is lower for Venus than for earth. Also note that the ground temperature Tg Te for Venus, with smaller differences for earth and Mars (Mercury has no atmosphere and Jupiter has no surface, but they are given here for additional points of comparison).

<table>
<thead>
<tr>
<th>planet</th>
<th>solar flux (W m(^{-2}))</th>
<th>orbit radius (10(^{11}) m)</th>
<th>albedo</th>
<th>T_e (K)</th>
<th>T_g (K)</th>
<th>Ground P (bar)</th>
<th># Layers</th>
<th>&quot;n&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>9200</td>
<td>0.6</td>
<td>0.058</td>
<td>442</td>
<td>442</td>
<td>~0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Venus</td>
<td>2600</td>
<td>1.1</td>
<td>0.77</td>
<td>227</td>
<td>750</td>
<td>90</td>
<td>118</td>
<td></td>
</tr>
<tr>
<td>Earth</td>
<td>1400</td>
<td>1.5</td>
<td>0.33</td>
<td>253</td>
<td>288</td>
<td>1</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Mars</td>
<td>600</td>
<td>2.3</td>
<td>0.15</td>
<td>216</td>
<td>240</td>
<td>0.007</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Jupiter §</td>
<td>49</td>
<td>7.8</td>
<td>0.58</td>
<td>98</td>
<td>(no surface)</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
</tbody>
</table>

§ Jupiter has no known solid surface, and internal sources of energy exceed solar input.

Summary of effects of atmospheric absorption in the infrared (terrestrial radiation) and albedo (for solar radiation)
The ground temperature in our ultra-simple model is given by
\[
T_g = [ n(T_g) + 1 ]^{1/4} T_e .
\]

We have indicated the possibility of feedback by noting that the number of absorbing "layers", n (also called the "optical thickness"), can depend on the temperature of the atmosphere. The effective temperature T_e depends on the albedo and on F_s, the solar flux, and doesn't change as long as these quantities are fixed. We know the relationship between T_e and albedo, thus
\[
T_g = [ [ n(T_g) + 1][1 - A(T_g) ] F_s/(4\sigma) ]^{1/4}
\]

and we have noted that the albedo A can also depend on temperature through formation of clouds, change in ice cover, etc., a different kind of feedback.

Note the equivalence of changes in albedo, which affect climate by changing the amount of solar radiation absorbed by the planet, and changes in n, which affect the trapping of terrestrial radiation and warming of the surface by back-radiation (the greenhouse effect). Both the greenhouse effect and feedback are completely natural phenomena essential for
maintaining the earth’s climate as we know it, and likely responsible for the large natural
climate variations of the past (e.g. ice ages). Concerns about **anthropogenic climate change** arise because the radiative properties of the atmosphere (amount of heat trapped and re-radiated, albedo) depend on **trace gases, aerosols, vegetation**, and other parameters that may be affected globally by humans.

**Effect of water vapor**

Water vapor is the most important "greenhouse gas". The *direct* influence of CO\(_2\) increases is small—about 2 W m\(^{-2}\). This may be compared with the overall exchanges in the energy budget of the earth: total solar flux is 1370 W m\(^{-2}\), on average over the whole earth about 365 W m\(^{-2}\) (shadow area is \(\pi R_e^2\), surface area is \(4\pi R_e^2\)) with about 2/3 absorbed (about 255 W m\(^{-2}\)).

**Effects of Clouds: Wild cards in climate prediction**

The concentration of carbon dioxide in the atmosphere has reached 360 ppm. This is the highest it has been any time in the last 400,000 years. It has increased from a pre-industrial atmospheric abundance of 278 ppm. We know that carbon dioxide is a greenhouse gas, therefore, it will result in an increase in the surface temperature. The warming could be enhanced when surface temperature leads to increased abundance of water vapor in the atmosphere.

**Cloud Greenhouse Effect: High vs. Low**

![Diagram of cloud greenhouse effect](image)
Since increased water vapor in the atmosphere may also lead to an increase in cloud cover, one difficulty in determining the influence of increased water vapor on the surface temperature is predicting the impact of clouds on the global energy budget. Clouds have very high albedos and thus reflect more solar radiation. But they also absorb strongly in the infrared. As we will show below, it matters where in the atmosphere the clouds form. Low clouds act to cool the surface while high clouds warm the surface. Any attempt to estimate surface temperatures as a result of global warming has to be able to accurately predict the future change in cloud cover.

In the case of a high cloud, it is as if we have added another layer to the energy balance model. As a result, the surface temperature must increase. For the low cloud, this is not the case. Because the low cloud is close to the ground, convection between the cloud and the ground will try to bring the temperature of the cloud close to that of the ground. As a result, the cloud will be radiating to the atmosphere at the same rate as the ground did before the cloud was formed. Consequently, there will be no net warming. In addition, low clouds are more dense than high clouds and thus have higher albedos. An increase in the albedo will lead to a reduction in the solar energy absorbed by the ground and thus the surface temperature may decrease.

The formation of high clouds as a result of global warming would be a positive feedback which would further exacerbate the problem. On the other hand, low clouds would be a negative feedback which would act to stabilize the surface temperature.

**Atmospheric aerosols: Global cooling?**

Aerosols are suspended particles in the air which are small enough to resist gravitational sedimentation (i.e. they remain afloat despite the force of gravity acting on them). Aerosols can be solid, liquid, or a combination of both. They typically range in size from 0.1 to 1.0 micrometers. The main sources of aerosols are dust from the surface, sea spray (liquid droplets and solid sea-salt particles), volcanoes, forest fires, and anthropogenic combustion.

The size of aerosols is of the same magnitude as the wavelength of visible radiation. As a result, they efficiently scatter visible radiation. On days when the aerosol content of the atmosphere is high, visibility is usually significantly reduced. Without aerosols in the atmosphere, the visual range on Earth would be approximately 300 km (limited by scatter due to air molecules). An important source of aerosols in urban areas is the emission of sulfur dioxide (SO$_2$) from factories. Once in the atmosphere, SO$_2$ is oxidized to form sulfuric acid droplets (H$_2$SO$_4$) and other sulfate bearing aerosols.

Aerosols do not efficiently scatter IR radiation. But they scatter the incoming solar radiation, preventing it from reaching the surface. As a result, aerosols increase the albedo of the Earth and decrease the surface temperatures. The following figure shows the reduction in surface temperatures which occurred after the eruption of Mt Pinatubo in the Philippines in June 1991. The figure shows both the observed temperature change.
It is thought that the cooling caused by emission of combustion aerosols (mostly sulfate) may have largely canceled the warming by increased CO$_2$ over the past century. In the figure below we show the increase in sulfur emissions (labeled S) over the past century. Also shown are the observed change in surface temperatures in the Northern and Southern Hemispheres (labeled TNH and TSH respectively). As the sulfur emissions increased significantly, starting sometime around 1940-1950, the surface temperatures in the Northern Hemisphere stopped increasing and actually began decreasing. This change in the temperature trend is not visible in the Southern Hemisphere. However, most of the sulfur is emitted by the industries of the Northern Hemisphere therefore one would expect a larger temperature effect in the Northern Hemisphere.
Fig. 4. Trends in temperatures of the Southern and Northern Hemispheres and in other variables during the most recent century. See text for data sources. Curve identifications: Δ, NH volcanic dust; V, SH volcanic dust, ○, S; ◊, GHG; ●, SOI; +, TSH; □, regression fit to TSH; ×, TNH; ○, regression fit to TNH.
Summary: Feedbacks

Most feedbacks in the climate system are positive (amplifying):

1. **Water vapor feedback.** Higher T -> atmosphere holds more H₂O -> higher T -> ....
2. **Ice-albedo feedback** Higher T -> less snow/ice -> lower albedo -> higher T -> ....
3. **Vegetation/precipitation feedback** Drier climate -> less leaf area -> lower albedo -> higher T -> drier climate -> ....

Some feedbacks have uncertain sign (cloud/temperature/water vapor), and a few are negative.

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**Main points of this chapter**

- **The earth radiates energy back to space at the same rate that it absorbs energy from the sun.** Viewed from space, the earth is approximately a black body with an emission temperature of 253K.

The basic physics of the greenhouse effect is simple, and inescapable. If we add infrared absorbers to the atmosphere, the climate should warm. However, there are many complications that make it extremely difficult to determine how much the earth has warmed/should warm in the future due to addition of CO₂ and other greenhouse gasses. Complications include feedback effects and addition of materials that may change the earth's albedo.

- **Clouds can provide a considerable negative feedback to global warming.** Thus a 0.4% increase in cloud albedo over the Earth during the past century would have canceled the effect of the rise in CO₂. [Exercise: calculate by how much the Earth's temperature would change if the cloud albedo increased by 10%].
- **Feedbacks involving clouds are complicated!** When water vapor increases, it is not clear whether cloud cover will
  - increase (because higher water vapor - more condensation)
  - decrease (because higher water vapor - more precipitation)
- **Clouds efficiently reflect solar radiation (albedo effect) but also absorb efficiently in the IR (greenhouse effect).** Whether a cloud has a net cooling or heating effect depends on its altitude. Low clouds (stratus) have a net cooling effect while high clouds (cirrus) have a net warming effect.
- **Aerosols are suspended particles in the air.** Their size is typically of the same magnitude as the wavelength of visible radiation.
- **Aerosols scatter visible radiation efficiently.** As a result, they can significantly reduce visibility. Because they scatter visible radiation, aerosols reduce the penetration of solar radiation to the surface and increase the albedo of the Earth, and thus cool the surface.
- **The earth's albedo may also be raised by vegetation change, especially deforestation, or reduced by reforestation.**