Week 3: Greenhouse Effect (Chap. 3) - Overview

Major Themes
Radiation: A form of energy (specifically, electromagnetic waves). All matter emits radiation. Also, all coupled-systems have energy flowing through them and, for the Earth system (as for any planet), this is radiation. Shortwave radiation flows in from the sun and longwave radiation flows out from the Earth.

Radiation and matter interactions: radiation can be absorbed, reflected, or transmitted by matter. All matter emits radiation.

Planetary energy balance (see Equations, below). Note that we supplemented the text by calculating a key quantity: the average flux of energy into and out of the Earth system (240 W/m²).

Atmospheric composition: major constituents (Table 3-2) and major greenhouse gases (Table 3-3).

Atmospheric structure: variation of pressure and temperature with height and the two most important layers for our purposes – troposphere and stratosphere (Figure 3-9).

Why the greenhouse gases absorb infrared (or longwave) radiation but most atmospheric gases (N₂ and O₂) do not (Figures 3-12 through 3-15).

The vast majority of the natural greenhouse effect is due to water – both water vapor and liquid water (clouds). Water is also a major player in the global warming problem (the anthropogenic enhancement of the greenhouse effect). However, water in the atmosphere is part of the climate system feedbacks; unlike CO₂, it cannot be considered a forcing.

Clouds act both to trap infrared radiation (like the greenhouse gases) and to reflect solar radiation. Thus, clouds have both warming and cooling effects. The net effect depends mostly on cloud height. (High clouds warm; low clouds cool.)

Major climate feedbacks: water vapor (positive), ice-albedo (positive), clouds (sign uncertain but generally thought to be positive).

Climate forcing and climate sensitivity: For a given forcing (e.g. the 4.4 W/m² associated with doubling CO₂) how much will the Earth’s surface temperature change? This is the forcing/response relationship for the Earth’s climate. Clearly, a critical parameter for anticipating the effects of rising CO₂. (Note: The text discusses this in terms of the feedback factor, which is equivalent. See Equations, below, for additional information.)

Equations

Albedo
The fraction of light reflected by a surface. In terms of a planet, the albedo is the fraction of sunlight (or solar energy) that is reflected back out to space – i.e. that is not absorbed by the planet.

\[ A = \frac{E_{\text{reflected}}}{E_{\text{total}}} \]

so \n
\[ 1 - A = \frac{E_{\text{absorbed}}}{E_{\text{total}}} \]

where \( E_{\text{total}} \) is the total light impinging upon the surface or planet.
Global Energy Balance

for a planet which is neither warming nor cooling

\[ E_{IN} = E_{OUT} \]

where, \( E_{IN} \) is the shortwave, solar radiation (a form of energy) absorbed and \( E_{OUT} \) is the longwave, infrared radiation emitted by the planet (both in units of W/m\(^2\))

Solar energy absorbed by Earth-atmosphere system (cf text p 41-42)

First, energy per unit surface area (or flux) is

\[ E \ (W/m^2) = \frac{\text{total energy (Watts)}}{\text{surface area (meters squared)}} \]

Then, the solar energy absorbed per unit Earth surface area is,

\[ E_{IN} = \frac{S_0}{4} (1 - A) = \frac{1370}{4} (1 - 0.30) = 240 \ (W/m^2) \]

where, \( S_0 \) is the solar constant (1370 W/m\(^2\)), 4 is a geometrical factor to convert from the area of a circle to the surface area of a sphere, and \( A \) is the planetary albedo (fraction of sunlight reflected to space – about 0.30 for the Earth).

Note: This quantity (240 W/m\(^2\)) is the average energy flux into and out of the Earth-Atmosphere system. It is a key property of the planet. (For some reason, the text never quantifies it.)

Energy emitted by a blackbody: Stephan-Boltzmann Law

\[ E = \sigma T^4 \]

where E is the energy emitted in W/m\(^2\), T is the temperature of the body in degrees Kelvin (K) and \( \sigma \) is the Stephan-Boltzmann constant (5.67x10\(^{-8}\))

Demonstration and Quantification of the Greenhouse Effect (cf text p. 41-42)

Now we can calculate the effective radiating temperature of the Earth, \( T_e \) – that is, the temperature of a blackbody that would produce the amount of energy radiated by Earth. According to the S-B Law, the energy emitted by the Earth-atmosphere system is,

\[ E_{OUT} = \sigma T_e^4 \]

and, by energy balance (that is, \( E_{OUT} \) must equal \( E_{IN} \) at equilibrium):

\[ E_{OUT} = E_{IN} = 240 \ (W/m^2) \]

Allowing us to solve for the \( T_e \) (using a bit of algebra):

\[ T_e = \left( \frac{E_{IN}}{\sigma} \right)^{1/4} = \left( \frac{240}{5.67 \times 10^{-8}} \right)^{0.25} = 255.1 \ (K) \]

This effective radiating temperature (255 Kelvin or -18°C, well below freezing) is a real property of the planet, but is obviously not the same as the average surface temperature, \( T_s \) (15°C, well above freezing). The fact that the global-annual average surface temperature is 33°C degrees warmer than the planetary equilibrium
temperature demonstrates significant heat-trapping by greenhouse gases in the Earth’s atmosphere.

Temperature change for doubled-CO2 in the “no-feedbacks” case
(supplements discussion in text p. 51)
Doubled CO₂ constitutes a climate forcing of 4.4 W/m², which means the infrared energy radiated to space would be reduced from 240 to 235.6 W/m². From the Stephan-Boltzmann Law, the current effective radiating temperature of the planet is 255.1 (K), as shown above, which is based on an emission of 240 W/m². If the emission to space were reduced to 235.6 W/m², the Earth would initially radiate as if it were a colder body:

\[ T_{e,\text{new}} = \left( \frac{235.6}{5.67 \times 10^{-8}} \right)^{0.25} = 253.9 \text{ (K)} \]

This shows that the Earth would have to warm up by 1.2 K (that is, 255.1 – 253.9) in order to restore radiative energy balance. The assumptions with this simple model are that the surface and every level in the atmosphere would warm by the same amount and that no other aspect of the atmosphere would change – in particular, water vapor, snow-cover, and clouds would not change. Thus, this is a “no-feedback” calculation of climate response.

Climate sensitivity and the feedback factor (supplements text discussion of feedbacks):
The feedback factor, \( f \), and climate sensitivity, \( \lambda \), are equivalent ways of talking about how much the Earth’s surface temperature will change for a given amount of climate forcing. The feedback factor is somewhat simpler and provides a better intuitive grasp (which is why the text uses this concept) but climate sensitivity is the term used in almost all of the scientific literature.

The feedback factor is defined by,

\[ \Delta T_{eq} = f \Delta T_0 \] (cf equation on p. 51 of text)

A positive feedback gives a feedback factor that is greater than 1 (that is, it amplifies the initial perturbation). Conversely, a negative feedback gives a feedback factor less than one (it dampens the initial perturbation).

The climate sensitivity parameter is defined by,

\[ \Delta T_{eq} = \lambda \Delta F \]

which is the fundamental equation relating climate forcing, \( \Delta F \) (W/m²), to climate response, \( \Delta T_{eq} \) (K). However, the numerical value and the units of \( \lambda \) are not very meaningful. But you should be aware of this term and of the above equation, as they are critical to the global warming debate.
**Key terms and concepts**

Absorption, reflection, transmission of radiation

*albedo*: fraction of incoming radiation that is reflected (see Equations)

*blackbody radiation*: a “blackbody” is an ideal case. It emits radiation exactly according to the Stephan-Boltzmann Law (see Equations). Thus, the S-B Law is an approximation for real objects, but a very good one in most cases.

*climate forcing*: an imposed change in planetary energy balance (W/m²)

*climate feedback, feedback factor, climate sensitivity*: (see Equations)

*climate model*: a mathematical representation of the present state of the Earth-atmosphere-ocean system and of the processes that govern how it changes over time or how it changes in response to a climate forcing. Climate models range in complexity from simple box models (e.g. Daisyworld) to full-blown 3-dimensional models, often called General Circulation Models (GCMs).

*effective radiating temperature of Earth, Tₑ*: temperature that an ideal blackbody would have if it emitted the same amount of infrared energy as the Earth

**Kelvin temperature scale**

*molecular absorption bands*: Why certain molecules are able to absorb infrared radiation. Involves molecular symmetry. If the molecule can vibrate or rotate in a way that moves electrical charges about, then it can absorb energy from the electromagnetic waves. Key examples are the 15-µm CO₂ vibrational absorption band and the 12-µm H₂O rotational absorption band. (µm: 1 millionth of a meter)

*shortwave vs longwave (or infrared) radiation*

*atmospheric structure*: lapse rate, troposphere, stratosphere

*atmospheric composition*: major constituents, trace constituents, greenhouse gases, water vapor and relative humidity

**A few handy numbers**

GAAST: global-annual-average surface temperature (our key climate index) or Tₛ

- Present value 288K or 15°C

  The natural greenhouse effect causes GAAST to be 33°C warmer than it would be without an atmosphere.

  - Observed change in GAAST over last century +0.6°C
  - Predicted change in GAAST over this century +1.5 to +4.5°C
  - Change in GAAST associated with ice-age about −5°C

Energy flowing through the Earth Climate System (Eᵢₙ = Eᵩᵢₚ at equilibrium)

- Energy flux at present 240 W/m²
- Doubled-CO₂ is an imposed change (forcing) of 4.4 W/m² (or ~2% change) [equivalent to turning up the sun by ~2%]