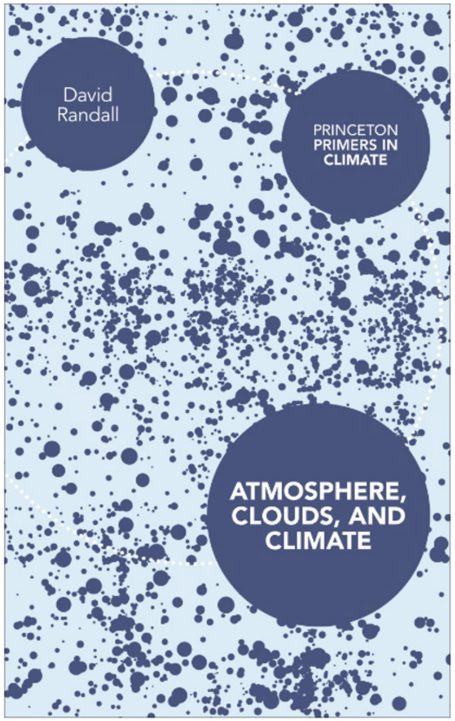
Atmosphere, Clouds, and Climate Introduction

AOSC 680

Ross Salawitch

Class Web Sites:
http://www2.atmos.umd.edu/~rjs/class/fall2022
https://umd.instructure.com/courses/1327017



Lecture 12

18 October 2022

Student Projects

- Each student will provide an 18 minute (12 to 15 slide) presentation on a research project, either 2, 6, or 8 December 2022
- Presentations will be in the same order as the discussions of the Princeton Primers in Climate (PPC) readings, to provide some level of proper “spacing”
- Those presenting towards the end of the PPC readings encouraged to get started soon on your research project
- Each student will also submit a 6 to 8 pages single spaced (not including reference list or figures) paper, n the same project, due at the class meeting that follows the in-class project presentation (or Mon 12 Dec for those presenting on 8 Dec)
- Project should be ***new work for this class*** but can be related to your dissertation or some other topic in which you’ve had prior interest
- Would like students to provide a **2 to 3 sentence description** of your research project by a week from today, by replying here: https://umd.instructure.com/courses/1327017/quizzes/1551279
- Happy to speak and/or exchange email with students about possible projects
- For emails, most appreciated if subject can begin with “AOSC 680:”
- If given a complete draft of your paper at least 7 calendar days prior to due date, I will provide back an edited "mark-up" you can use as input for final submission

Student Led Discussions of Princeton Primers In Climate

- I will provide a powerpoint file with all graphical elements (figures & tables)
- If you want to show text, scan either can the pages yourself, obtain an e-copy and take a screen capture, or give me at least 2 days notice of precisely which text passages you would like to use and I will provide
- If you would like to keep to “class” and “handout” mode for slides, I will be happy to print the “handout” version provided I have by at least 1 pm on day of presentation
- More than happy to have a meeting either in person (best time is after class; other times can be arranged) or Zoom to review a draft of your presentation

Chapter 1, Atmosphere, Clouds, and Climate

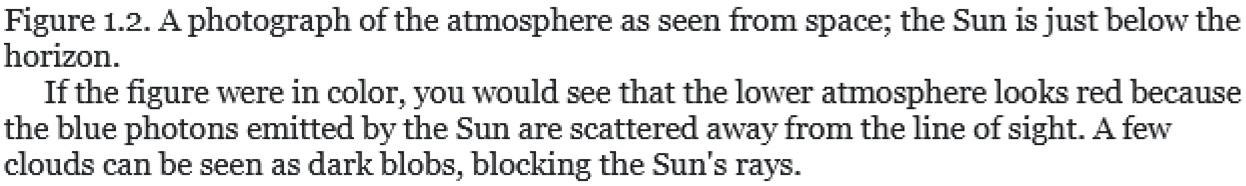


Figure 1.2. A photograph of the atmosphere as seen from space; the Sun is just below the horizon.

If the figure were in color, you would see that the lower atmosphere looks red because the blue photons emitted by the Sun are scattered away from the line of sight. A few clouds can be seen as dark blobs, blocking the Sun's rays.

Source: https://commons.wikimedia.org/wiki/File:Sunset_from_the_ISS.JPG

Chapter 1, Atmosphere, Clouds, and Climate

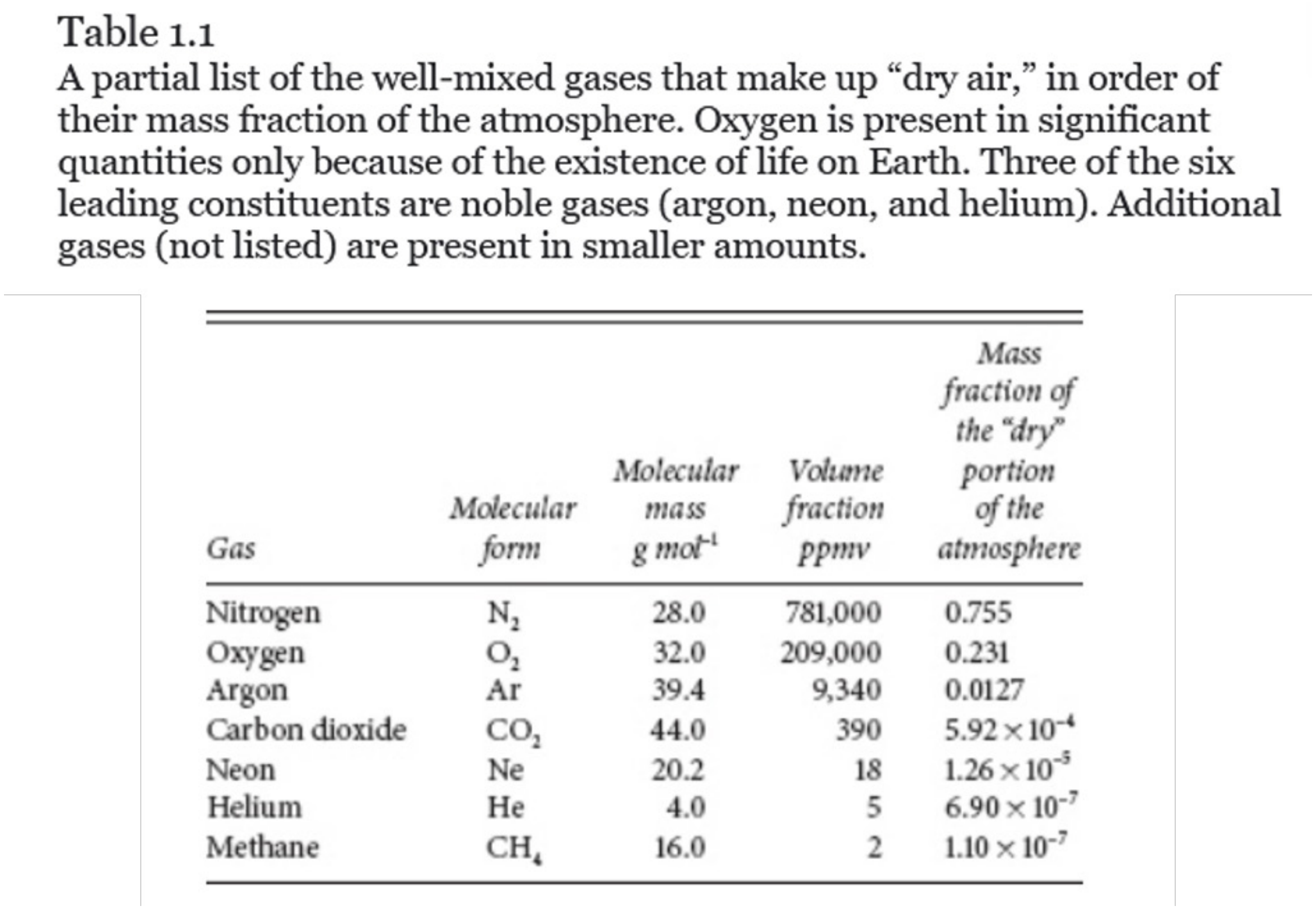


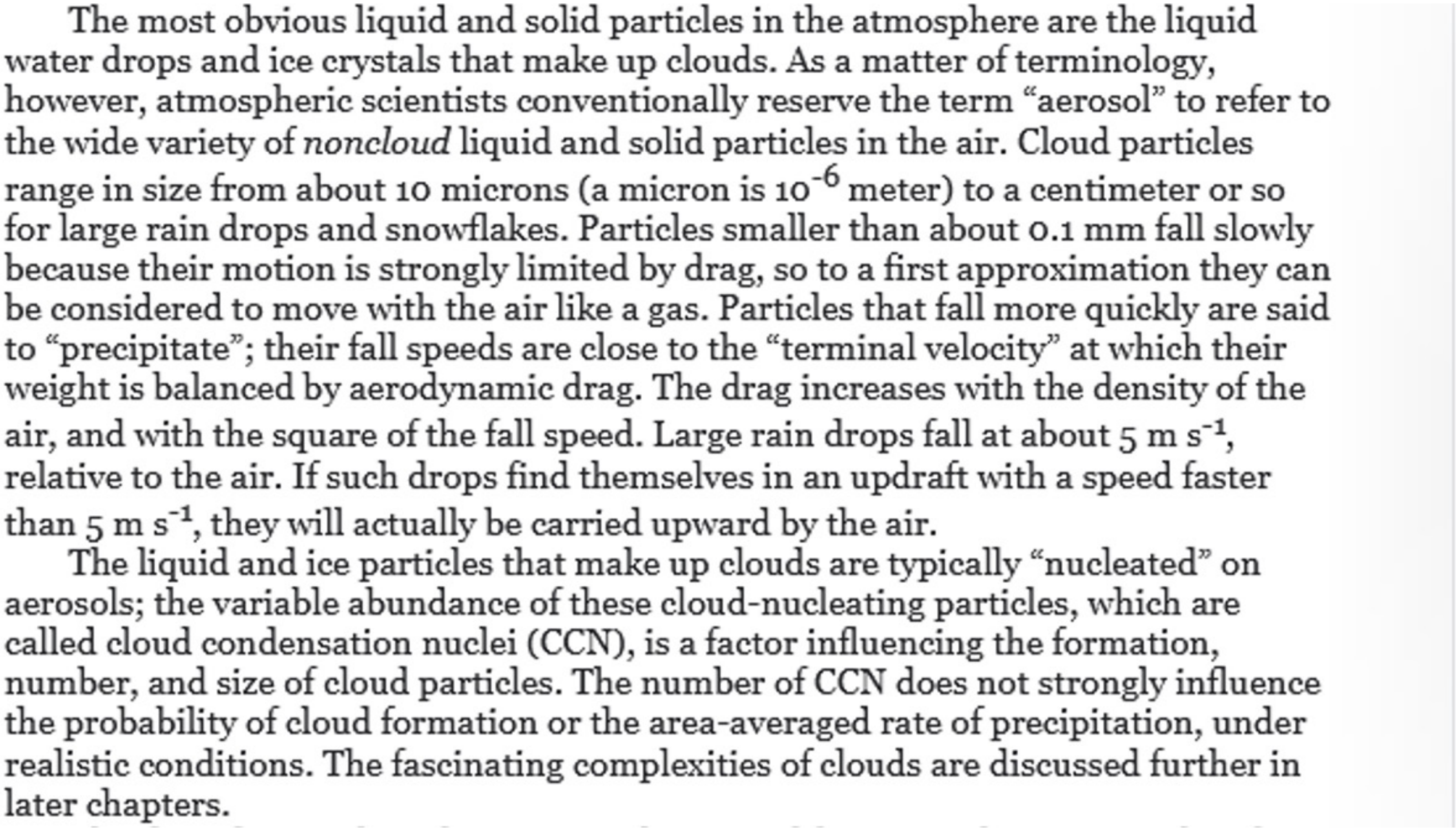
Table 1.1

A partial list of the well-mixed gases that make up "dry air," in order of their mass fraction of the atmosphere. Oxygen is present in significant quantities only because of the existence of life on Earth. Three of the six leading constituents are noble gases (argon, neon, and helium). Additional gases (not listed) are present in smaller amounts.

Gas	*Molecular form*	*Molecular mass g mol^{-1}*	*Volume fraction ppmv*	*Mass fraction of the "dry" portion of the atmosphere*
Nitrogen	N_2	28.0	781,000	0.755
Oxygen	O_2	32.0	209,000	0.231
Argon	Ar	39.4	9,340	0.0127
Carbon dioxide	CO_2	44.0	390	5.92×10^{-4}
Neon	Ne	20.2	18	1.26×10^{-5}
Helium	He	4.0	5	6.90×10^{-7}
Methane	CH_4	16.0	2	1.10×10^{-7}

Any surprise?

Chapter 1, Atmosphere, Clouds, and Climate



The most obvious liquid and solid particles in the atmosphere are the liquid water drops and ice crystals that make up clouds. As a matter of terminology, however, atmospheric scientists conventionally reserve the term “aerosol” to refer to the wide variety of *noncloud* liquid and solid particles in the air. Cloud particles range in size from about 10 microns (a micron is 10^{-6} meter) to a centimeter or so for large rain drops and snowflakes. Particles smaller than about 0.1 mm fall slowly because their motion is strongly limited by drag, so to a first approximation they can be considered to move with the air like a gas. Particles that fall more quickly are said to “precipitate”; their fall speeds are close to the “terminal velocity” at which their weight is balanced by aerodynamic drag. The drag increases with the density of the air, and with the square of the fall speed. Large rain drops fall at about 5 m s^{-1}, relative to the air. If such drops find themselves in an updraft with a speed faster than 5 m s^{-1}, they will actually be carried upward by the air.

The liquid and ice particles that make up clouds are typically “nucleated” on aerosols; the variable abundance of these cloud-nucleating particles, which are called cloud condensation nuclei (CCN), is a factor influencing the formation, number, and size of cloud particles. The number of CCN does not strongly influence the probability of cloud formation or the area-averaged rate of precipitation, under realistic conditions. The fascinating complexities of clouds are discussed further in later chapters.

Chapter 1, Atmosphere, Clouds, and Climate

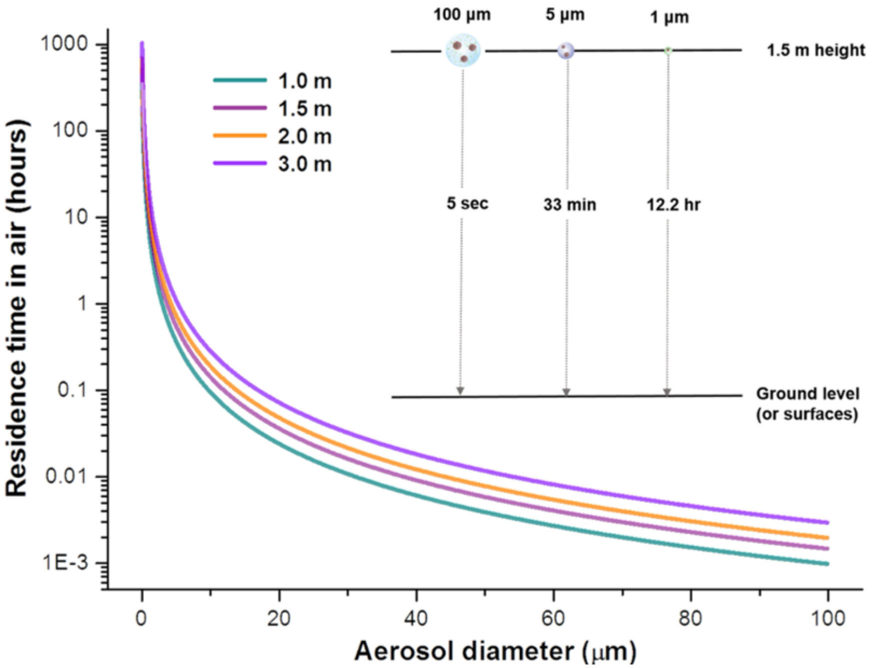
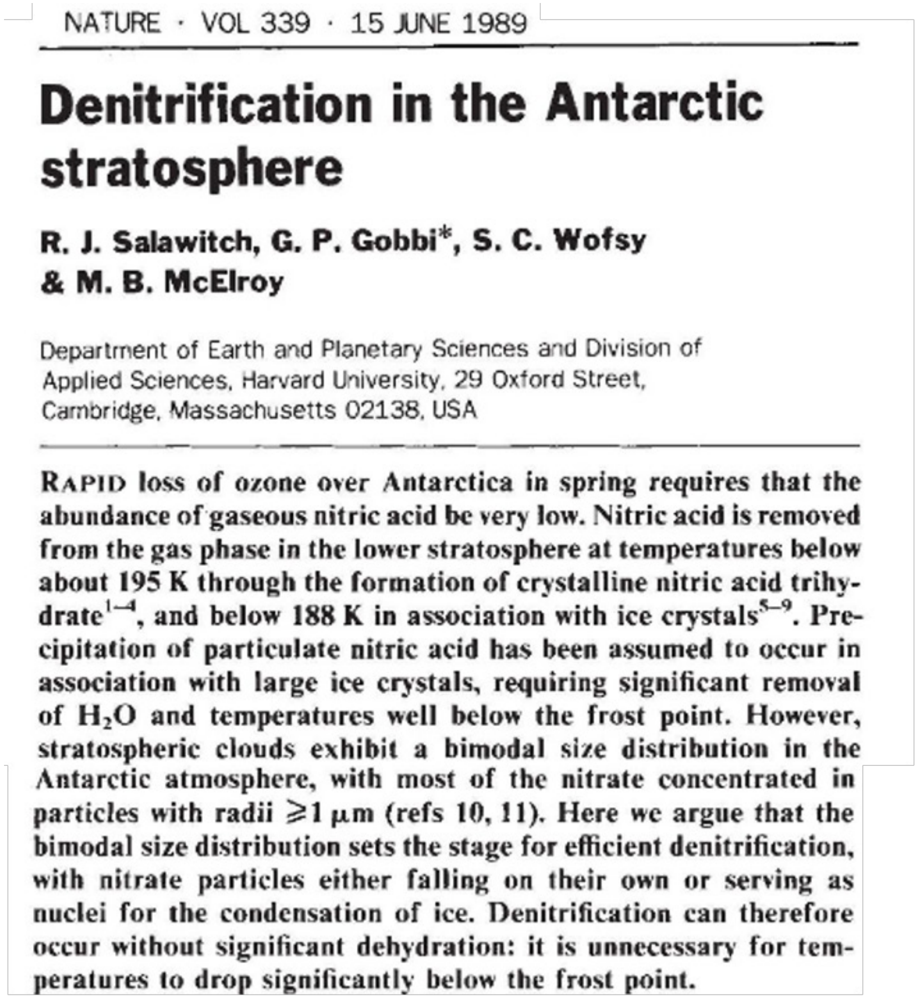


Fig. 3. How long can aerosols linger in air?

Residence time of aerosols of varying size in still air can be estimated from Stokes' law for spherical particles (*116*). For example, the time required for an aerosol of 100, 5, or 1 µm to fall to the ground (or surfaces) from a height of 1.5 m is 5 s, 33 min, or 12.2 hours, respectively.

https://www.science.org/doi/10.1126/science.abd9149

Chapter 1, Atmosphere, Clouds, and Climate



NATURE · VOL 339 · 15 JUNE 1989

Denitrification in the Antarctic stratosphere

R. J. Salawitch, G. P. Gobbi*, S. C. Wofsy & M. B. McElroy

Department of Earth and Planetary Sciences and Division of Applied Sciences, Harvard University, 29 Oxford Street, Cambridge, Massachusetts 02138, USA

RAPID loss of ozone over Antarctica in spring requires that the abundance of gaseous nitric acid be very low. Nitric acid is removed from the gas phase in the lower stratosphere at temperatures below about 195 K through the formation of crystalline nitric acid trihydrate[1–4], and below 188 K in association with ice crystals[5–9]. Precipitation of particulate nitric acid has been assumed to occur in association with large ice crystals, requiring significant removal of H_2O and temperatures well below the frost point. However, stratospheric clouds exhibit a bimodal size distribution in the Antarctic atmosphere, with most of the nitrate concentrated in particles with radii ≳1 μm (refs 10, 11). Here we argue that the bimodal size distribution sets the stage for efficient denitrification, with nitrate particles either falling on their own or serving as nuclei for the condensation of ice. Denitrification can therefore occur without significant dehydration: it is unnecessary for temperatures to drop significantly below the frost point.

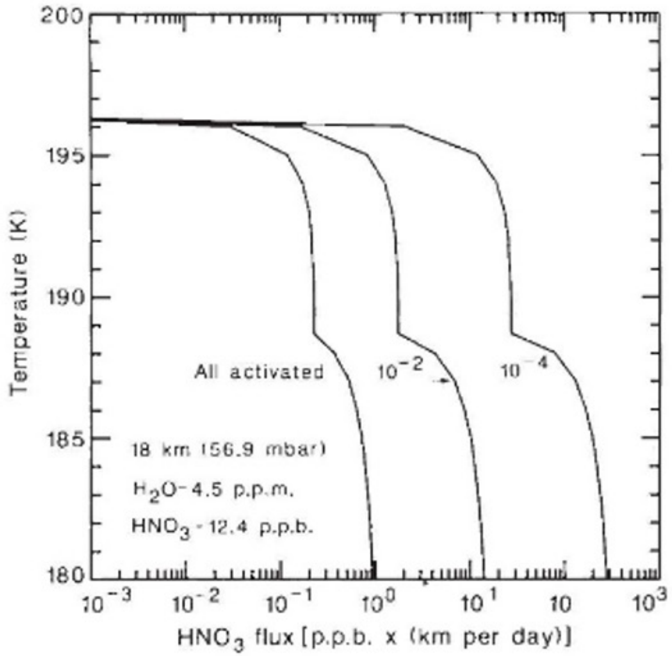


FIG. 1 The flux of nitric acid in sedimenting particles is shown as a function of temperature for various numbers of activated nuclei, expressed as a fraction of the initial condensation nuclei (assumed density 10 cm^{-3}). The air parcel was assumed to be at an altitude of 18 km and to maintain thermodynamic equilibrium with its environment at all times. Condensation of NAT begins at 196.3 K; the same particles activated during the growth of NAT were assumed to be activated when water ice forms (188.7 K). The analysis focuses on vapour pressures and particle densities in clouds after condensation, when vapour and solid phases will be approximately at equilibrium. Therefore the lower temperatures ($\Delta T \approx 1$ K) required to activate background aerosols are not explicitly considered.

https://www.nature.com/articles/339525a0

Chapter 1, Atmosphere, Clouds, and Climate

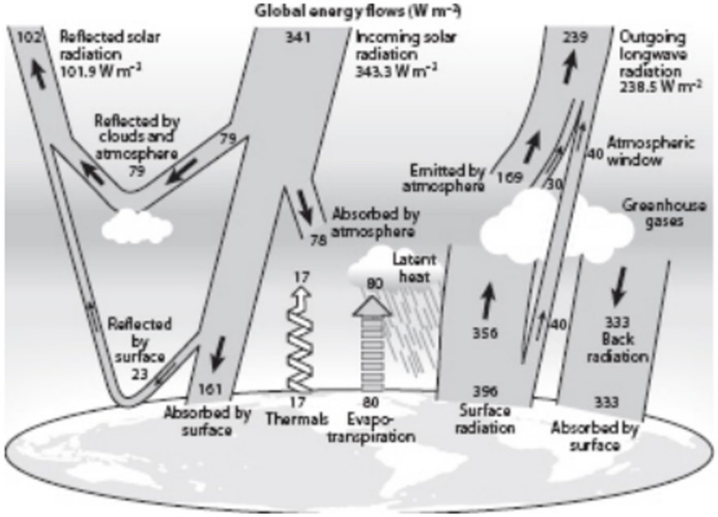
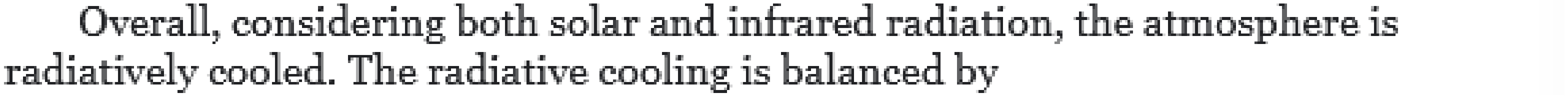


Figure 1.3. An overview of the flow of energy in the climate system.
The global annual mean Earth's energy budget for the March 2000 to May 2004 period (W m^{-2}). The broad arrows indicate the schematic flow of energy in proportion to their importance.
Source: Based on a figure in Trenberth et al. (2009).



Overall, considering both solar and infrared radiation, the atmosphere is radiatively cooled. The radiative cooling is balanced by

Chapter 2, Atmosphere, Clouds, and Climate

What word describes this angle?

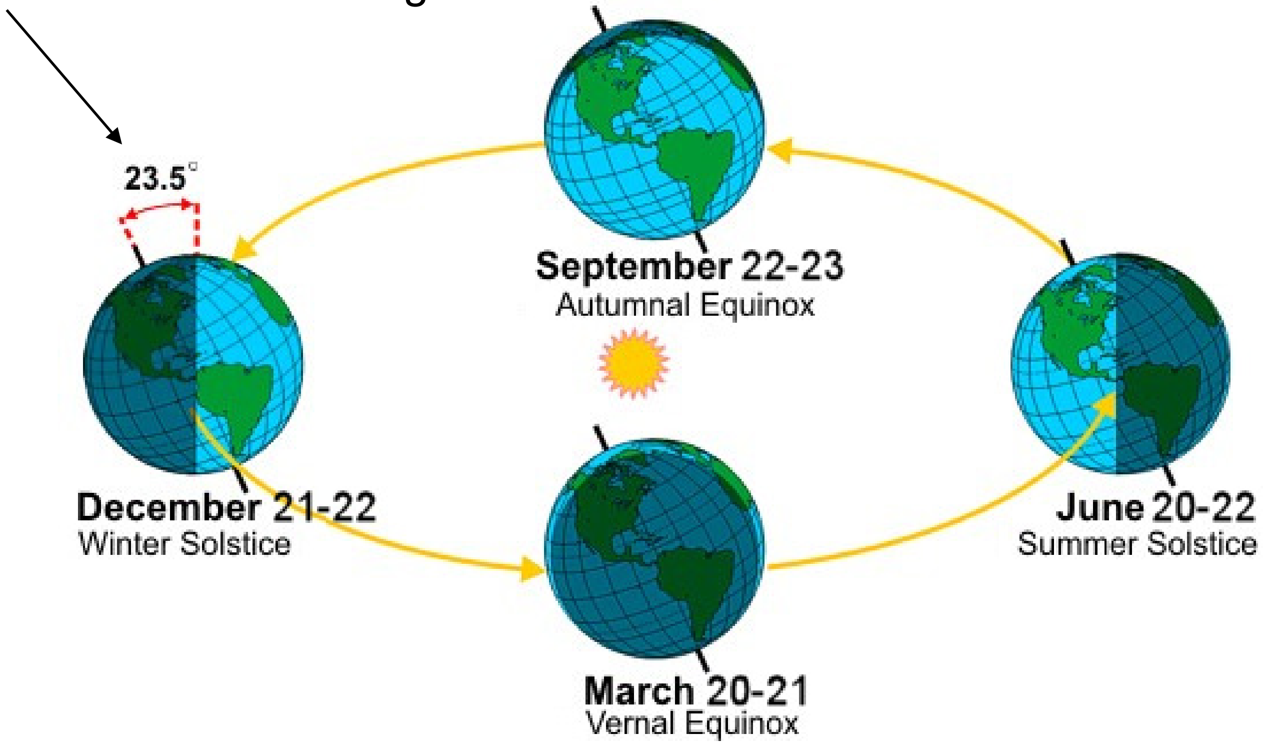
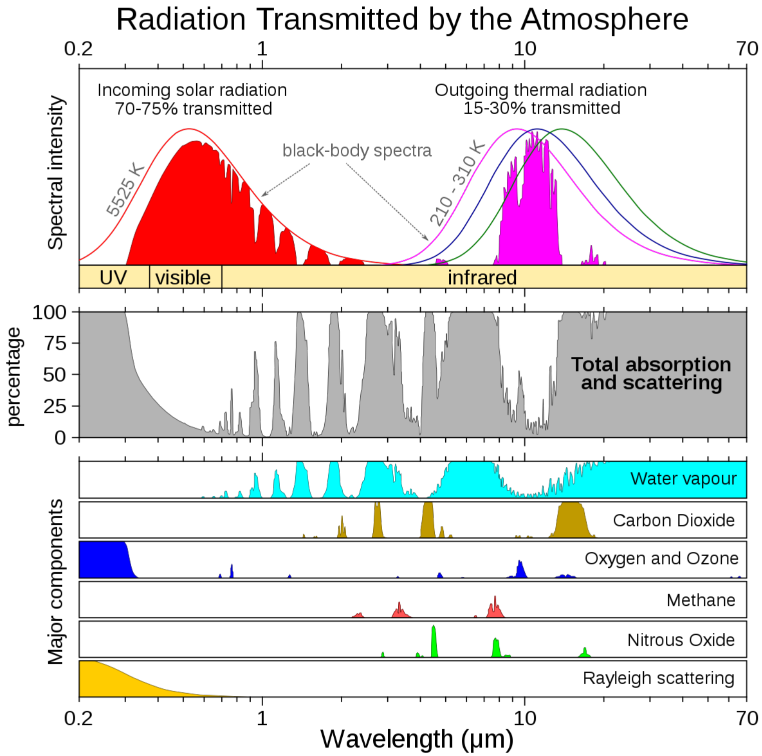


Figure 2.1. Changes in the Sun-Earth geometry as the Earth moves in its orbit. The Earth's axis is tilted with respect to the plane of its orbit. As the tilted Earth revolves around the Sun, changes in the distribution of sunlight cause the succession of seasons.

Source: https://www.weather.gov/images/cle/Education/EarthOrbit.png

Chapter 2, Atmosphere, Clouds, and Climate

Can someone talk us through this image?



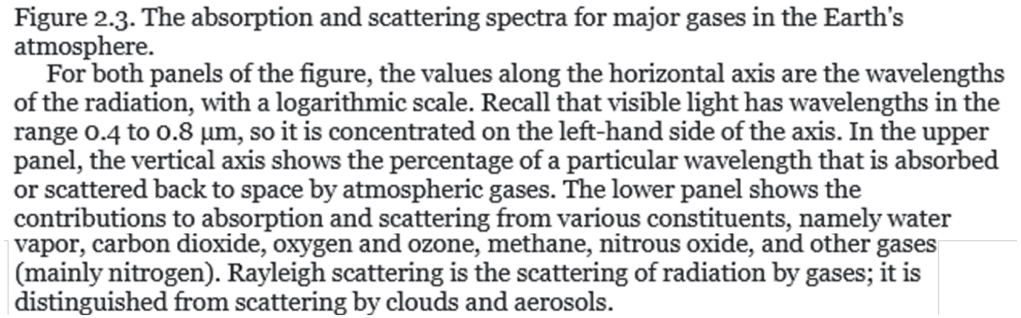


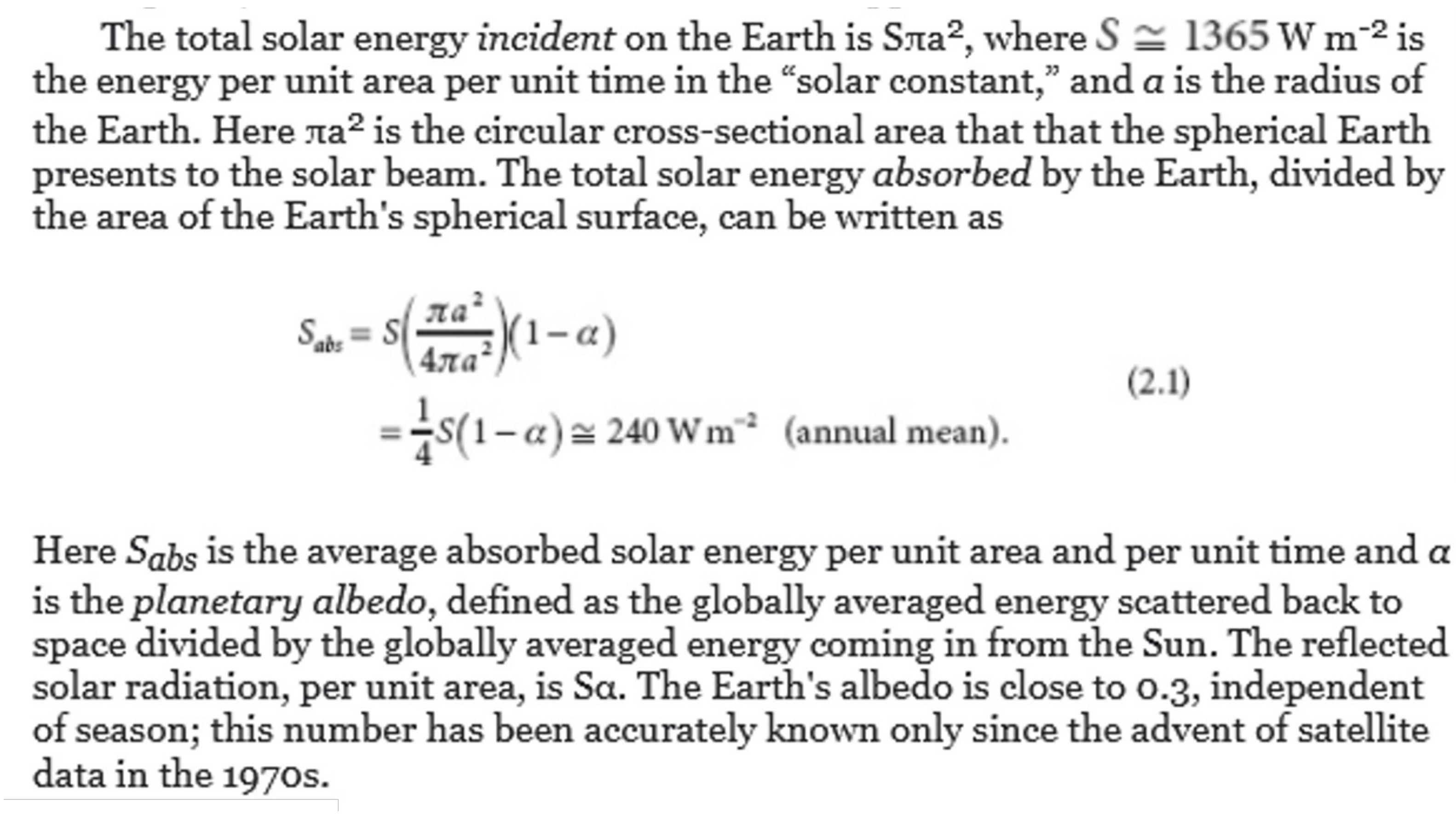
Figure 2.3. The absorption and scattering spectra for major gases in the Earth's atmosphere.

For both panels of the figure, the values along the horizontal axis are the wavelengths of the radiation, with a logarithmic scale. Recall that visible light has wavelengths in the range 0.4 to 0.8 µm, so it is concentrated on the left-hand side of the axis. In the upper panel, the vertical axis shows the percentage of a particular wavelength that is absorbed or scattered back to space by atmospheric gases. The lower panel shows the contributions to absorption and scattering from various constituents, namely water vapor, carbon dioxide, oxygen and ozone, methane, nitrous oxide, and other gases (mainly nitrogen). Rayleigh scattering is the scattering of radiation by gases; it is distinguished from scattering by clouds and aerosols.

Source: https://upload.wikimedia.org/wikipedia/commons/thumb/5/5e/Atmospheric_Transmission-en.svg/1200px-Atmospheric_Transmission-en.svg.png

Chapter 2, Atmosphere, Clouds, and Climate

How does this passage compare to our prior description?



The total solar energy *incident* on the Earth is $S\pi a^2$, where $S \cong 1365\ \mathrm{W\,m^{-2}}$ is the energy per unit area per unit time in the "solar constant," and a is the radius of the Earth. Here πa^2 is the circular cross-sectional area that that the spherical Earth presents to the solar beam. The total solar energy *absorbed* by the Earth, divided by the area of the Earth's spherical surface, can be written as

$$\begin{aligned} S_{abs} &= S\left(\frac{\pi a^2}{4\pi a^2}\right)(1-\alpha) \\ &= \frac{1}{4}S(1-\alpha) \cong 240\ \mathrm{W\,m^{-2}} \quad \text{(annual mean).} \end{aligned} \qquad (2.1)$$

Here S_{abs} is the average absorbed solar energy per unit area and per unit time and α is the *planetary albedo*, defined as the globally averaged energy scattered back to space divided by the globally averaged energy coming in from the Sun. The reflected solar radiation, per unit area, is $S\alpha$. The Earth's albedo is close to 0.3, independent of season; this number has been accurately known only since the advent of satellite data in the 1970s.

Chapter 2, Atmosphere, Clouds, and Climate

Can someone talk us through this table?

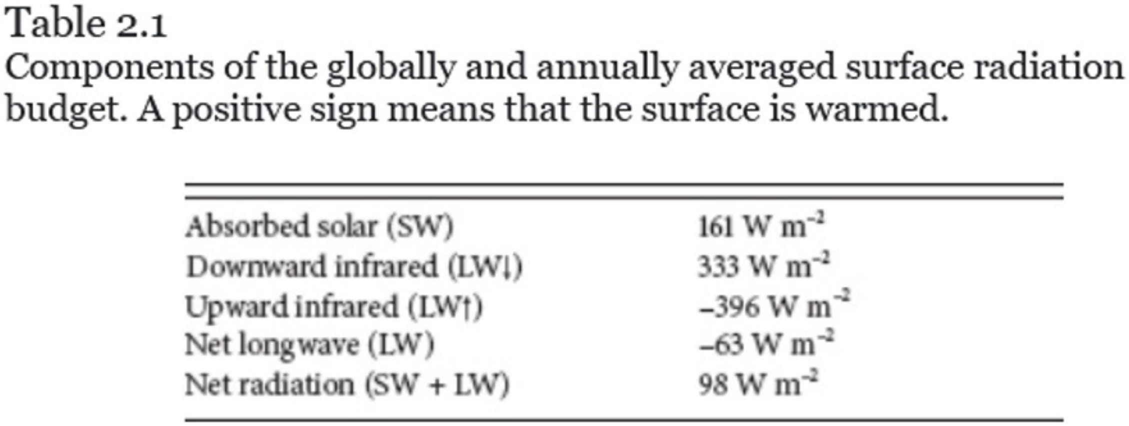


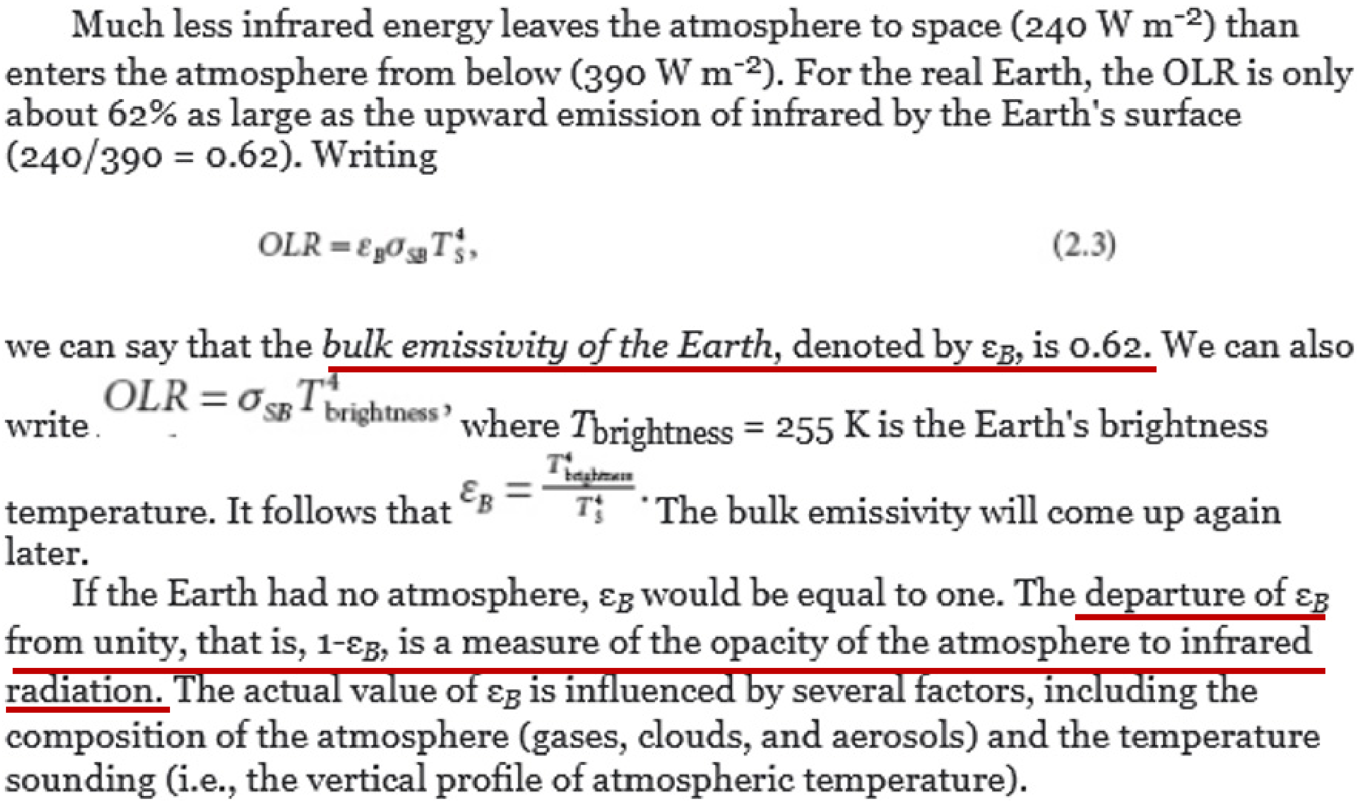
Table 2.1

Components of the globally and annually averaged surface radiation budget. A positive sign means that the surface is warmed.

Absorbed solar (SW)	161 W m^{-2}
Downward infrared (LW↓)	333 W m^{-2}
Upward infrared (LW↑)	–396 W m^{-2}
Net longwave (LW)	–63 W m^{-2}
Net radiation (SW + LW)	98 W m^{-2}

Chapter 2, Atmosphere, Clouds, and Climate

What is the value and meaning of the bulk emissivity of Earth's atmosphere?



Much less infrared energy leaves the atmosphere to space (240 W m^{-2}) than enters the atmosphere from below (390 W m^{-2}). For the real Earth, the OLR is only about 62% as large as the upward emission of infrared by the Earth's surface (240/390 = 0.62). Writing

$$OLR = \varepsilon_B \sigma_{SB} T_S^4, \qquad (2.3)$$

we can say that the *bulk emissivity of the Earth*, denoted by ε_B, is 0.62. We can also write $OLR = \sigma_{SB} T_{\text{brightness}}^4$, where $T_{\text{brightness}}$ = 255 K is the Earth's brightness temperature. It follows that $\varepsilon_B = \frac{T_{\text{brightness}}^4}{T_S^4}$. The bulk emissivity will come up again later.

If the Earth had no atmosphere, ε_B would be equal to one. The departure of ε_B from unity, that is, $1-\varepsilon_B$, is a measure of the opacity of the atmosphere to infrared radiation. The actual value of ε_B is influenced by several factors, including the composition of the atmosphere (gases, clouds, and aerosols) and the temperature sounding (i.e., the vertical profile of atmospheric temperature).

Chapter 2, Atmosphere, Clouds, and Climate

What did folks think of the simplified two layer model?

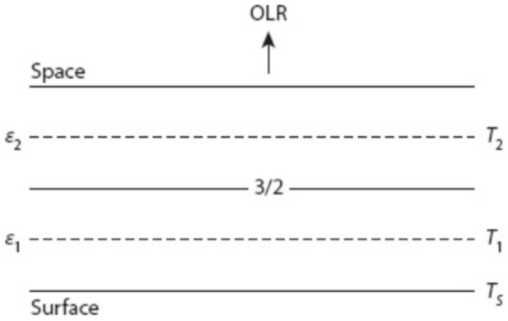
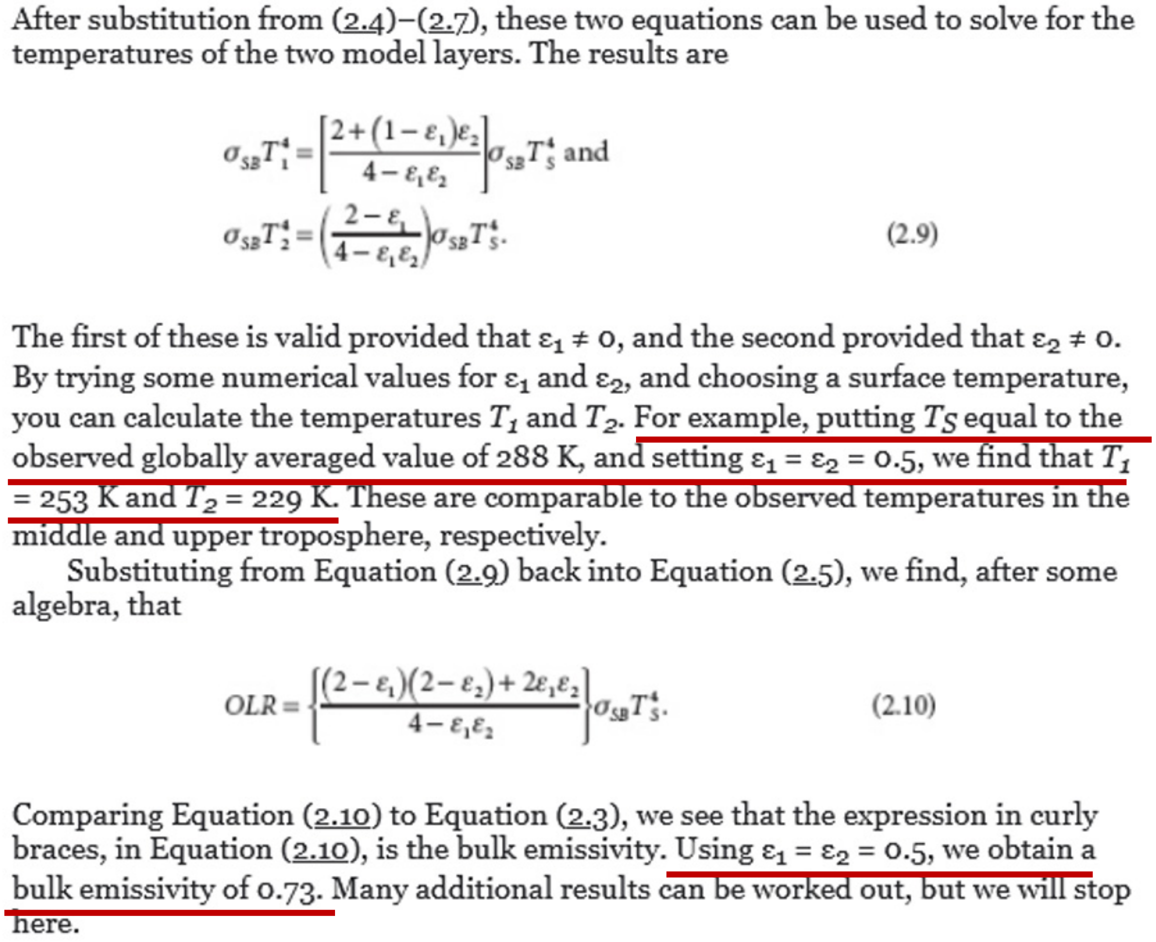


Figure 2.4. An idealized model in which the atmosphere is represented by just two layers, with different temperatures and emissivities.

The lower layer is denoted by subscript 1, and the upper layer by subscript 2. The interface between the two layers is denoted by subscript 3/2.



After substitution from (2.4)–(2.7), these two equations can be used to solve for the temperatures of the two model layers. The results are

$$\sigma_{SB}T_1^4 = \left[\frac{2+(1-\varepsilon_1)\varepsilon_2}{4-\varepsilon_1\varepsilon_2}\right]\sigma_{SB}T_S^4 \text{ and}$$

$$\sigma_{SB}T_2^4 = \left(\frac{2-\varepsilon_1}{4-\varepsilon_1\varepsilon_2}\right)\sigma_{SB}T_S^4. \qquad (2.9)$$

The first of these is valid provided that $\varepsilon_1 \neq 0$, and the second provided that $\varepsilon_2 \neq 0$. By trying some numerical values for ε_1 and ε_2, and choosing a surface temperature, you can calculate the temperatures T_1 and T_2. For example, putting T_S equal to the observed globally averaged value of 288 K, and setting $\varepsilon_1 = \varepsilon_2 = 0.5$, we find that $T_1 = 253$ K and $T_2 = 229$ K. These are comparable to the observed temperatures in the middle and upper troposphere, respectively.

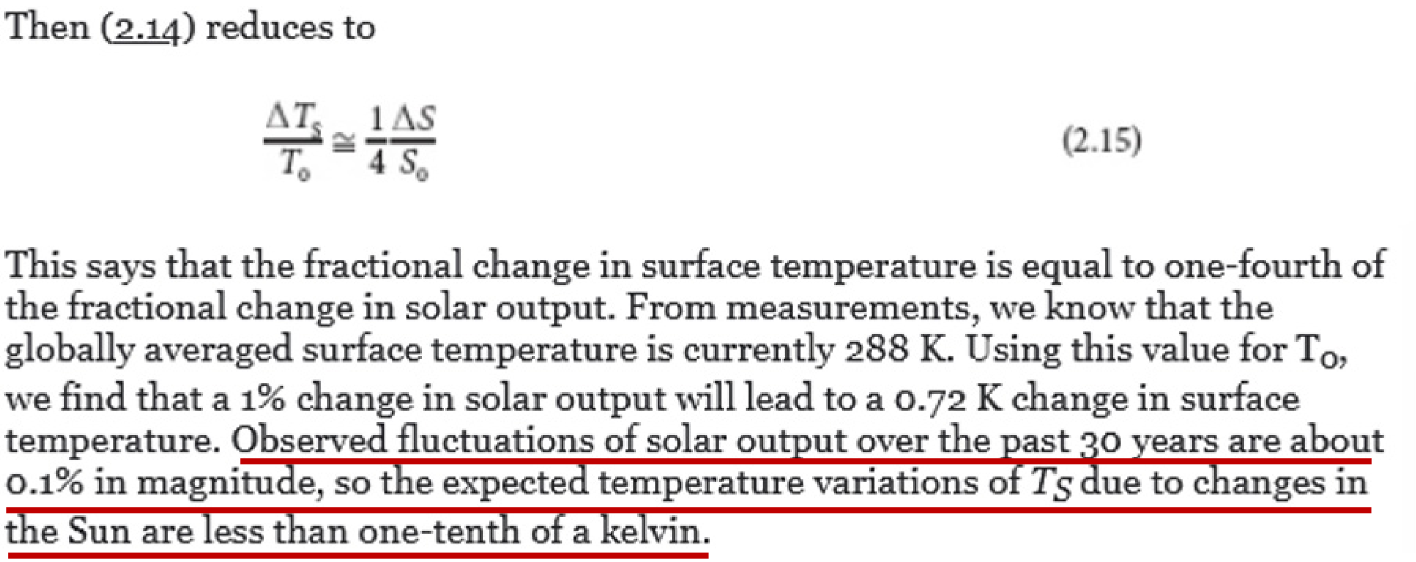
Substituting from Equation (2.9) back into Equation (2.5), we find, after some algebra, that

$$OLR = \left\{\frac{(2-\varepsilon_1)(2-\varepsilon_2)+2\varepsilon_1\varepsilon_2}{4-\varepsilon_1\varepsilon_2}\right\}\sigma_{SB}T_S^4. \qquad (2.10)$$

Comparing Equation (2.10) to Equation (2.3), we see that the expression in curly braces, in Equation (2.10), is the bulk emissivity. Using $\varepsilon_1 = \varepsilon_2 = 0.5$, we obtain a bulk emissivity of 0.73. Many additional results can be worked out, but we will stop here.

Chapter 2, Atmosphere, Clouds, and Climate

Let’s look at the solar model, in terms of prior class material:



Then (2.14) reduces to

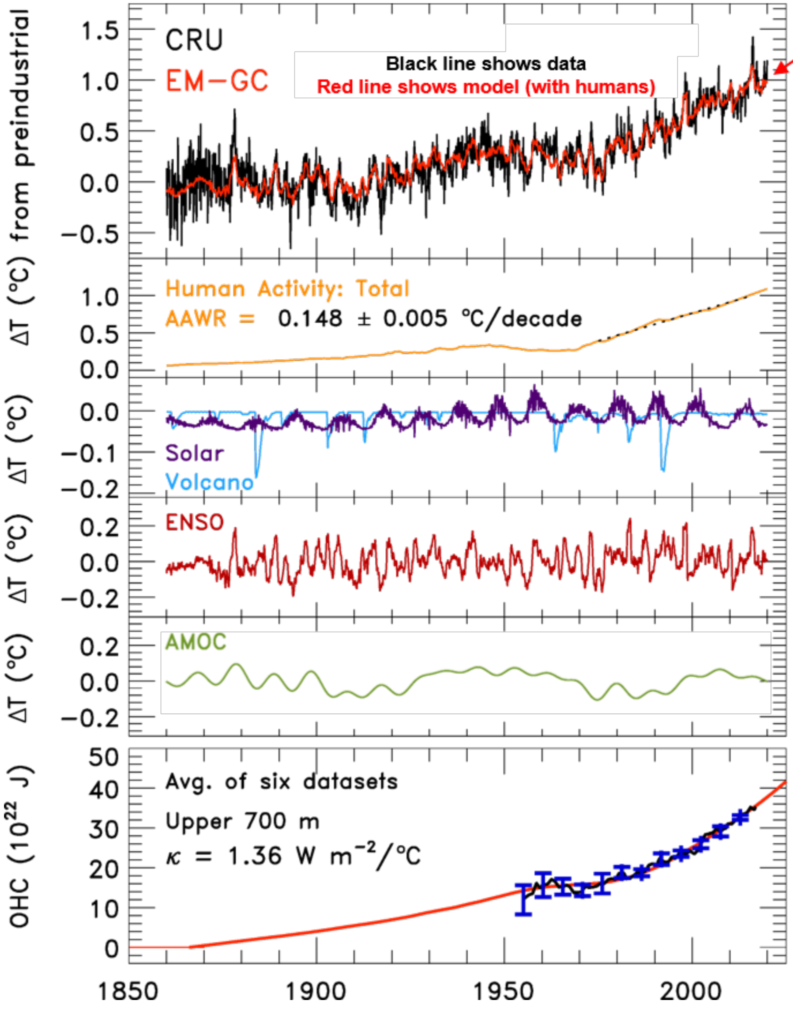
$$\frac{\Delta T_S}{T_o} \cong \frac{1}{4}\frac{\Delta S}{S_o} \tag{2.15}$$

This says that the fractional change in surface temperature is equal to one-fourth of the fractional change in solar output. From measurements, we know that the globally averaged surface temperature is currently 288 K. Using this value for T_O, we find that a 1% change in solar output will lead to a 0.72 K change in surface temperature. Observed fluctuations of solar output over the past 30 years are about 0.1% in magnitude, so the expected temperature variations of T_S due to changes in the Sun are less than one-tenth of a kelvin.

Chapter 2, Atmosphere, Clouds, and Climate

Let’s look at the solar model, in terms of prior class material:

Lecture 2:



$$\Delta T_{MDL\,i} = (1+\gamma)\left(\frac{GHG\ RF_i + LUC\ RF_i + Aerosol\ RF_i}{\lambda_p}\right) + C_0 + C_1 \times SOD_{i-6} + C_2 \times TSI_{i-1} + C_3 \times ENSO_{i-2} + C_4 \times AMOC_i - \left(\frac{Q_{OCEAN_i}}{\lambda_p}\right)$$

where:

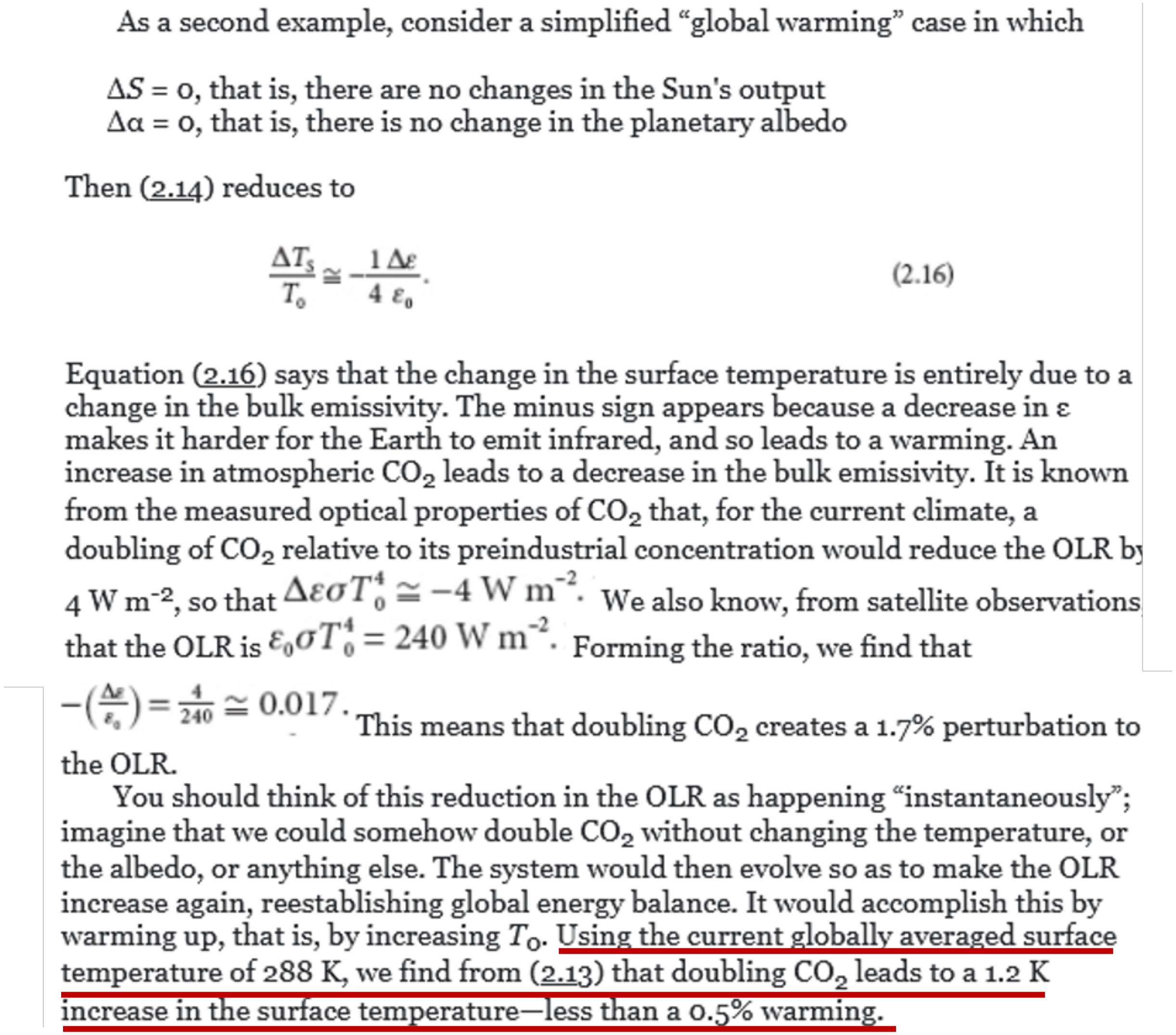
i denotes month
$\lambda_p = 3.2\ \mathrm{W\ m^{-2}\,°C^{-1}}$
$1+\gamma = \{1 - \lambda_\Sigma/\lambda_p\}^{-1}$
GHG RF = RF due to all anthropogenic GHGs
LUC RF = RF due to Land Use Change
Aerosol RF = RF due to Tropospheric Aerosols
SOD = Stratospheric Optical Depth
TSI = Total Solar Irradiance
ENSO = El Niño Southern Oscillation
AMOC = Atlantic Meridional Overturning Circulation
Q_{OCEAN} = Ocean heat export =
$\kappa(1+\gamma)\{\Delta T_{MDL\,i} - \Delta T_{OCEAN\ SURFACE\,i}\}$

CRU: Climate Research Unit of East Anglia, United Kingdom
EM-GC: Empirical Model of Global Climate, Univ of Maryland

Canty *et al*., 2013 https://www.atmos-chem-phys.net/13/3997/2013/acp-13-3997-2013.html
McBride *et al*., 2021 https://esd.copernicus.org/articles/12/545/2021
Nicholls *et al*., 2021 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020EF001900
Figure provided by Laura McBride.

Chapter 2, Atmosphere, Clouds, and Climate

Let’s look at the GHG model, in terms of prior class material:



As a second example, consider a simplified “global warming” case in which

$\Delta S = 0$, that is, there are no changes in the Sun's output
$\Delta\alpha = 0$, that is, there is no change in the planetary albedo

Then (2.14) reduces to

$$\frac{\Delta T_S}{T_0} \cong -\frac{1}{4}\frac{\Delta\varepsilon}{\varepsilon_0}. \qquad (2.16)$$

Equation (2.16) says that the change in the surface temperature is entirely due to a change in the bulk emissivity. The minus sign appears because a decrease in ε makes it harder for the Earth to emit infrared, and so leads to a warming. An increase in atmospheric CO_2 leads to a decrease in the bulk emissivity. It is known from the measured optical properties of CO_2 that, for the current climate, a doubling of CO_2 relative to its preindustrial concentration would reduce the OLR by 4 W m^{-2}, so that $\Delta\varepsilon\sigma T_0^4 \cong -4\ \mathrm{W\ m^{-2}}$. We also know, from satellite observations that the OLR is $\varepsilon_0\sigma T_0^4 = 240\ \mathrm{W\ m^{-2}}$. Forming the ratio, we find that $-\left(\frac{\Delta\varepsilon}{\varepsilon_0}\right) = \frac{4}{240} \cong 0.017$. This means that doubling CO_2 creates a 1.7% perturbation to the OLR.

You should think of this reduction in the OLR as happening “instantaneously”; imagine that we could somehow double CO_2 without changing the temperature, or the albedo, or anything else. The system would then evolve so as to make the OLR increase again, reestablishing global energy balance. It would accomplish this by warming up, that is, by increasing T_0. Using the current globally averaged surface temperature of 288 K, we find from (2.13) that doubling CO_2 leads to a 1.2 K increase in the surface temperature—less than a 0.5% warming.

Chapter 2, Atmosphere, Clouds, and Climate

Let’s look at the GHG model, in terms of prior class material:
Lecture 4:

$$\Delta \mathrm{T} \approx \frac{1}{4\,\sigma\,\mathrm{T}^3}\,\Delta \mathrm{RF}$$

Earth’s atmosphere is slightly more complicated, than a pure black body, as explained for example at http://zebu.uoregon.edu/ph311/lec06.html

So: $$\lambda = \frac{1}{4\,\sigma\,\mathrm{T}^3}$$

$\lambda_P \approx 0.3$ K / (W m^{-2})

Here: P refers to Planck Response Function

$$\Delta \mathrm{T} \approx 0.3\,\frac{\mathrm{K}}{\mathrm{W\,m^{-2}}}\,\Delta \mathrm{RF}$$

$$\Delta \mathrm{RF}_{\text{Doubling CO2}} \approx 5.35\ \mathrm{W\,m^{-2}}\ \ln\left(\frac{\mathrm{CO_2}^{\,Final}}{\mathrm{CO_2}^{\,Initial}}\right) = 3.7\ \mathrm{W\,m^{-2}}$$

$$\Delta \mathrm{T} \approx 0.3\,\frac{\mathrm{K}}{\mathrm{W\,m^{-2}}}\,\Delta \mathrm{RF} = 0.3 \times 3.7\ \mathrm{W\,m^{-2}} = \boxed{}$$