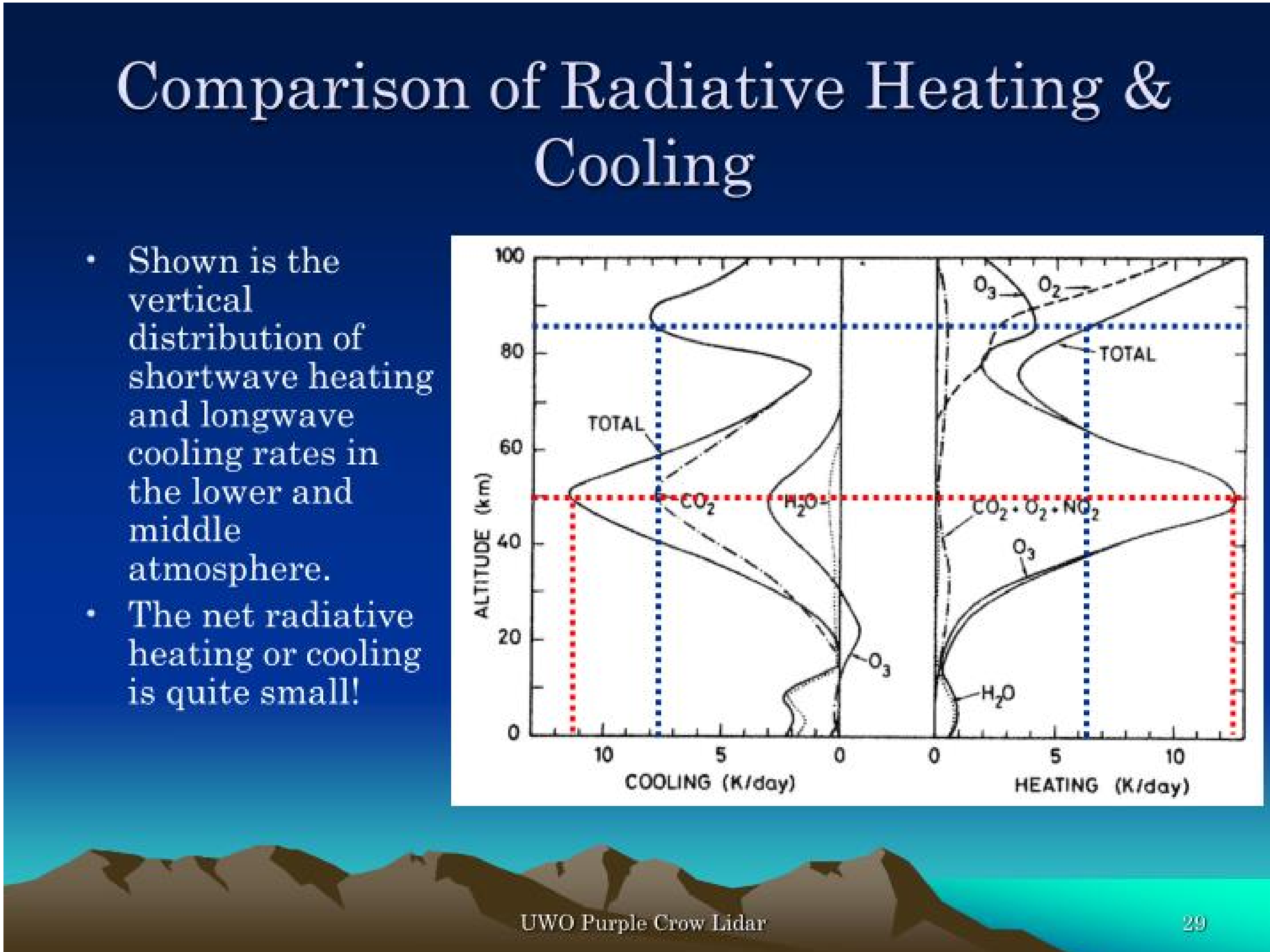
PHY2505S
Atmospheric Radiative Transfer and Remote Sounding

Lecture 6

- A Simple Greenhouse Model
- Terrestrial Fluxes: Schwarzchild's Equation Revisited
- The Two-Stream Model

Atmospheric Heating Rates



Bob Sica, UWO, https://www.slideserve.com/bena/uwo-s-purple-crow-lidar-studies-atmospheric-change-powerpoint-ppt-presentation

The Greenhouse Effect

- CO_2, H_2O, CH_4, O_3 $\rightarrow$ naturally radiatively active gases
- The fundamental reason for the existence of the greenhouse effect is that the temperature decreases with altitude in the troposphere.
- Radiatively active gases, as well as clouds, absorb the radiation emitted by the warmer surface, while their emission of radiation to space occurs at cooler atmospheric temperatures.
- The trapping of the radiation by radiatively active molecules produces an increase in the surface temperature of about 33°C (assuming no change in albedo when atmosphere is removed…).
- Recall: $$F(1-A) = 4\,\varepsilon_{infrared}\,\sigma\,T_e^4$$
  - $\rightarrow$ This gives T_e ~255 K (-18°C) *(with F_{sun}=1367 W m^{-2}, A=0.3, ε=1)*
  - $\rightarrow$ Using T_S ~288 K (15°C), the atmosphere traps ~33°C.

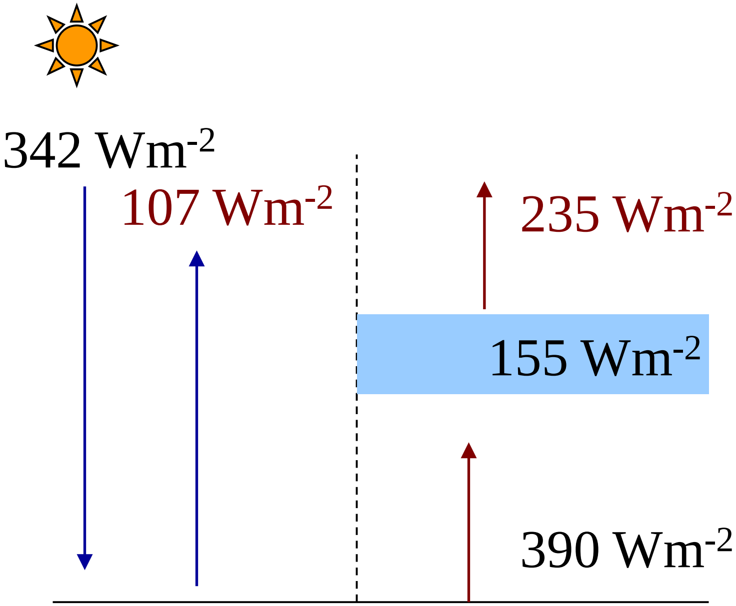
The Greenhouse Effect

CO_2 is active in the infrared spectral region

Increase in CO_2 leads to a decrease in the infrared transparency of the atmosphere

Increase in the surface temperature

NOT LINEAR!



- 155 W m^{-2} is trapped in the atmosphere
  - → represents the greenhouse effect
- Major players
  - → water vapour, CO_2, N_2O, O_3, CFCs, CH_4, HCFCs, HFCs, …

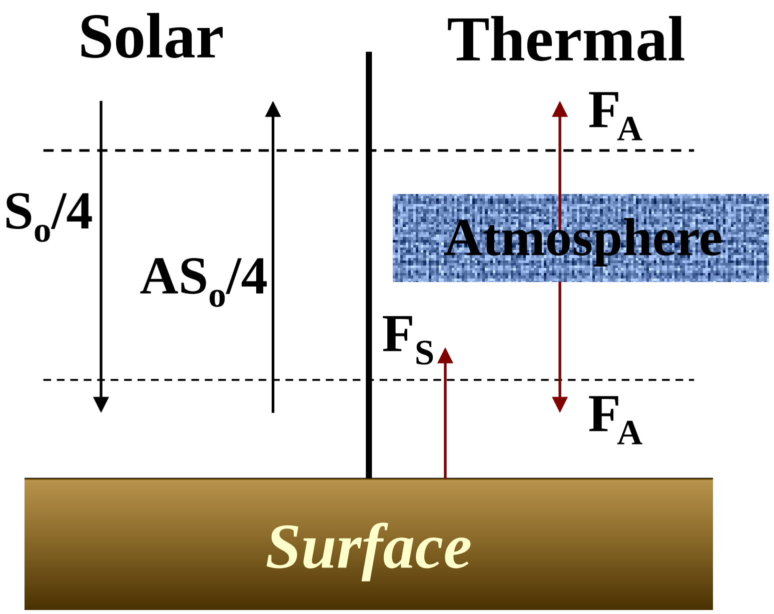
A Simple Greenhouse Model

Let's add the atmosphere to our simple radiative equilibrium model – a Half-Dimensional Climate Model

Question: How?

- Treat the atmosphere as a simple thin shell covering the planet.
- "Unroll" the sphere to obtain a planar diagram.
- Solar input to this plane: the average (over all orbital and global positions) input on a unit area of the planar surface: $S_o / 4$

  where $S_o = F_o$ is the solar constant. and factor of 4 = ratio of disk area to surface area of a sphere



Incident Solar Radiation

- Total output from the sun: $Q = 3.87 \times 10^{26}$ W

- Solar constant at Earth: $S_o = Q / 4\pi R^2_{earth\text{-}sun} \cong 1368\ W/m^2$
  where $R_{earth\text{-}sun} = 1.5 \times 10^{11}$ m

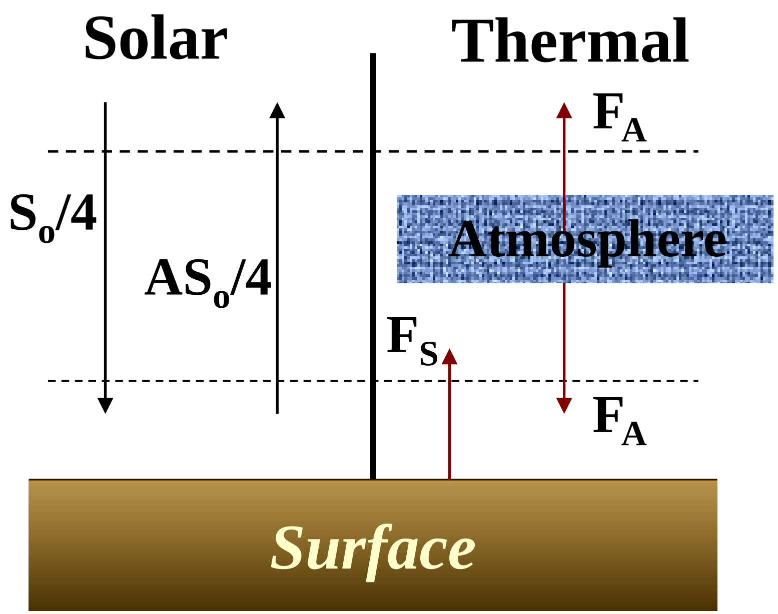
- Average incoming solar flux density / unit area at Earth:
  = energy intercepted per unit time / surface area
  $= (\pi r^2 S_o) / (4\pi r^2) = S_o/4 = 342\ W/m^2$

A Simple Greenhouse Model

Hypothesis:

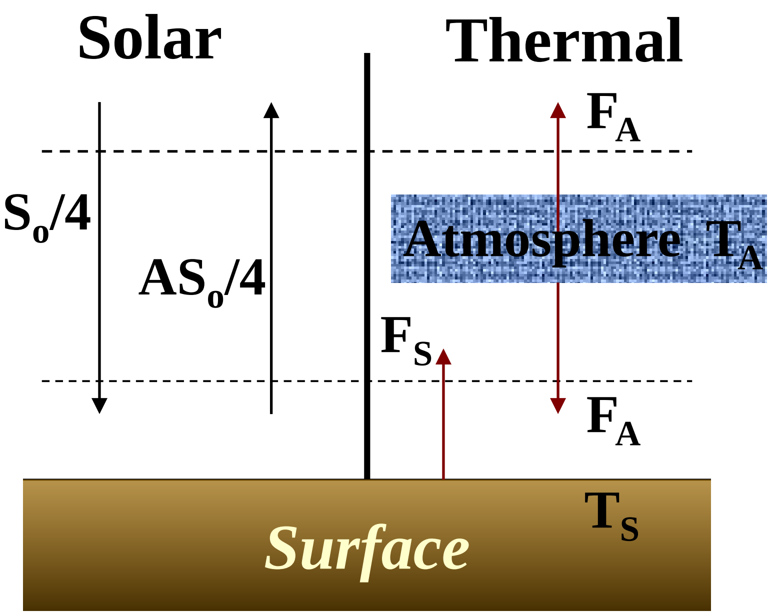
- Atmosphere is a planar layer of material that is
  - → transparent to solar radiation
  - → opaque to thermal radiation

Definitions:



- $S_o/4$ is the average solar input (W/m^2)
- A is the planetary albedo provided entirely by ground reflection.
- F_S is the infrared flux density emitted by the surface: $F_S = \sigma T_S^4$
- F_A is the infrared flux density emitted by the atmosphere (as would be seen by a distant radiometer): $F_A = \sigma T_A^4 = \sigma T_e^4$ (so $T_A = T_e$)
- $\varepsilon = 1$ (everything in the thermal region is considered to be black).

Same Diagram, Slightly Different Symbols



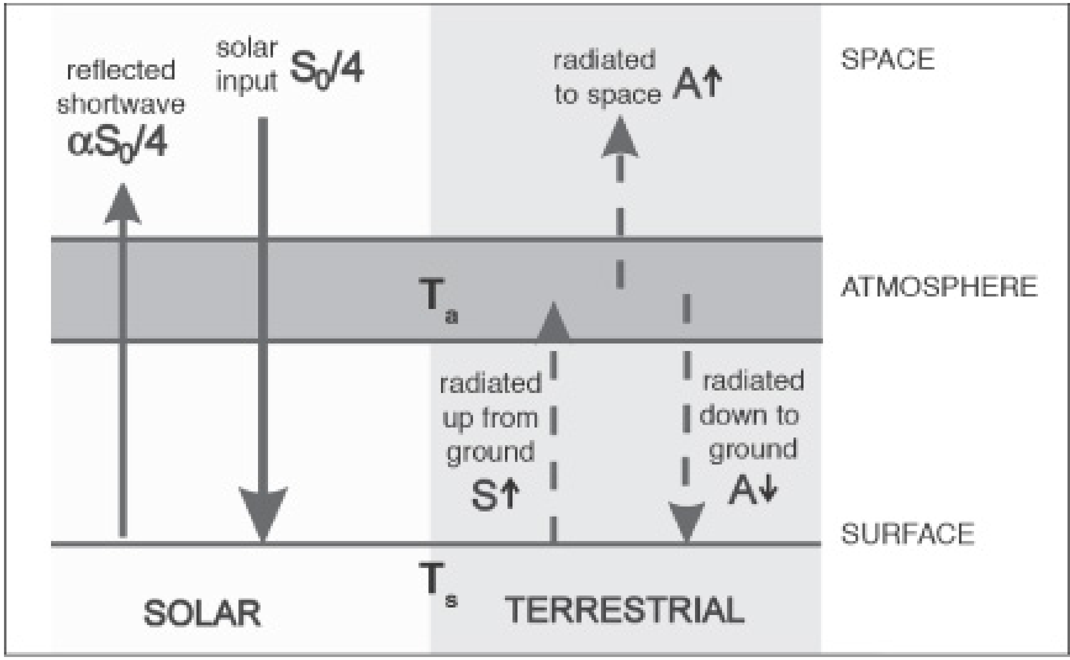


Figure 2.7: The simplest greenhouse model, comprising a surface at temperature T_s, and an atmospheric layer at temperature T_a, subject to incoming solar radiation $S_o/4$. The terrestrial radiation upwelling from the ground is assumed to be completely absorbed by the atmospheric layer.

Marshall and Plumb

A Simple Greenhouse Model - 3

- Writing down the equation for vertical energy transfer above the atmosphere and stating that the atmosphere/planet system is in radiative equilibrium:

$$S_o/4 = AS_o/4 + F_A$$

IR flux density emitted by the atmosphere

Planetary albedo

Average solar flux density

- Below the atmosphere:

$$S_o/4 + F_A = AS_o/4 + F_S$$

$$(AS_o/4 + F_A) + F_A = AS_o/4 + F_S$$

$$F_S = 2F_A$$

$$\sigma T_S^4 = 2\sigma T_e^4$$

- The surface temperature is therefore: $T_S = 2^{1/4}\ T_e = 1.19\ T_e$

Some Consequences

- For Earth: $T_e = 255$ K ⟶ $T_S = 303$ K
  i.e., the surface temperature is higher than the effective radiating temperature of Earth
- This is entirely due to the absorption of infrared terrestrial radiation by the atmosphere, which in turn re-radiates this back down to the surface, thus increasing the net downward radiative flux density at the surface
- The flux density emitted by the atmosphere (F_A) is very large, comparable to the solar flux density:

$$F_A = (1 - A)S_o / 4$$

- Actual mean T_S is 288 K, so this simple model is an overestimation
  - → Not all solar radiation incident at TOA reaches the surface
  - → Not all radiation emitted by the surface is absorbed by the atmosphere

A Leaky Greenhouse

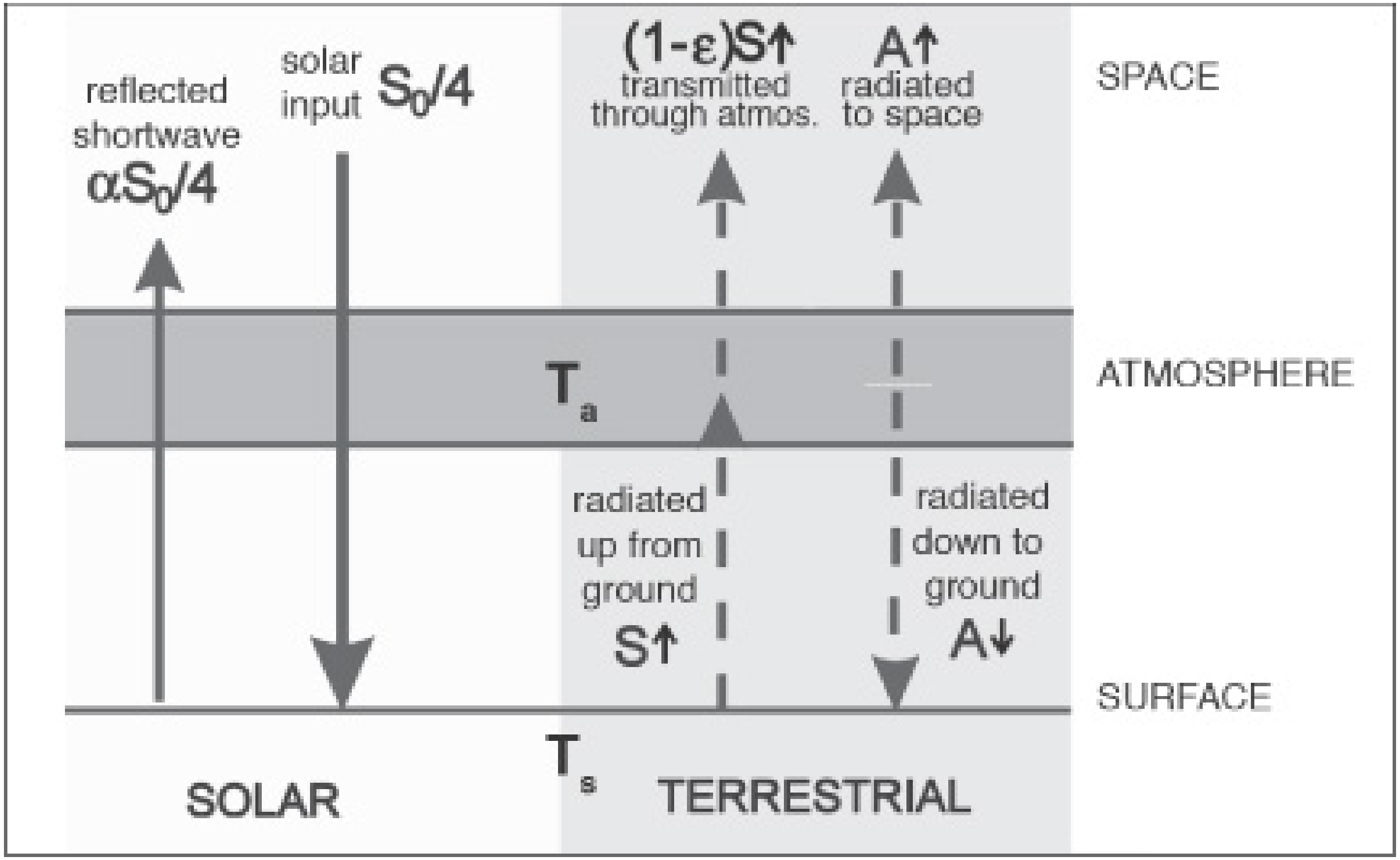


Figure 2.8: A leaky greenhouse. In contrast to Fig. 2.7, the atmosphere now absorbs only a fraction, ε, of the terrestrial radiation upwelling from the ground.

$S = F_S$

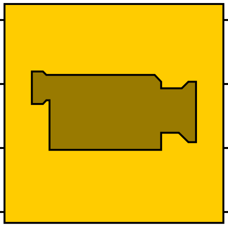
$A = F_A$

α = albedo A

ε = IR emissivity = absorptivity of the atmosphere

Marshall and Plumb

A Leaky Greenhouse



Derivation follows Marshall and Plumb, Chapter 2

A More Opaque Greenhouse

- Now imagine an atmosphere with a layer that absorbs all infrared radiation passing through it
  - → Space and the surface no longer see the same atmospheric layer
- We can also add a second opaque layer
- A correct model would include many layers, clouds, layer-by-layer absorption, and treat each wavelength and layer separately

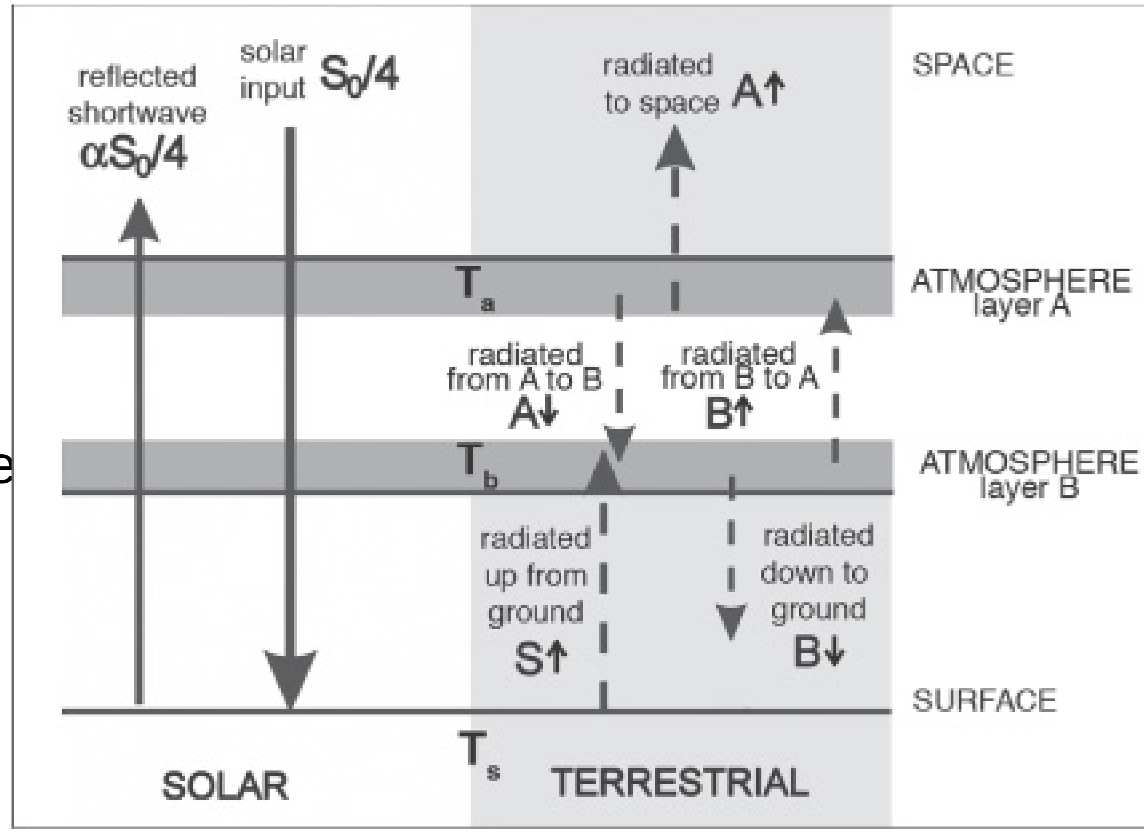


Figure 2.9: An "opaque" greenhouse made up of two layers of atmosphere. Each layer completely absorbs the IR radiation impinging on it.

Marshall and Plumb

Radiative Equilibrium Profile

This is the mean atmospheric temperature profile if heat transport in the atmosphere occurred only through radiative transfer.

The discontinuity at the surface is because most solar radiation is absorbed at the surface, but does not occur in the real atmosphere because of dynamical heat transport – convection.

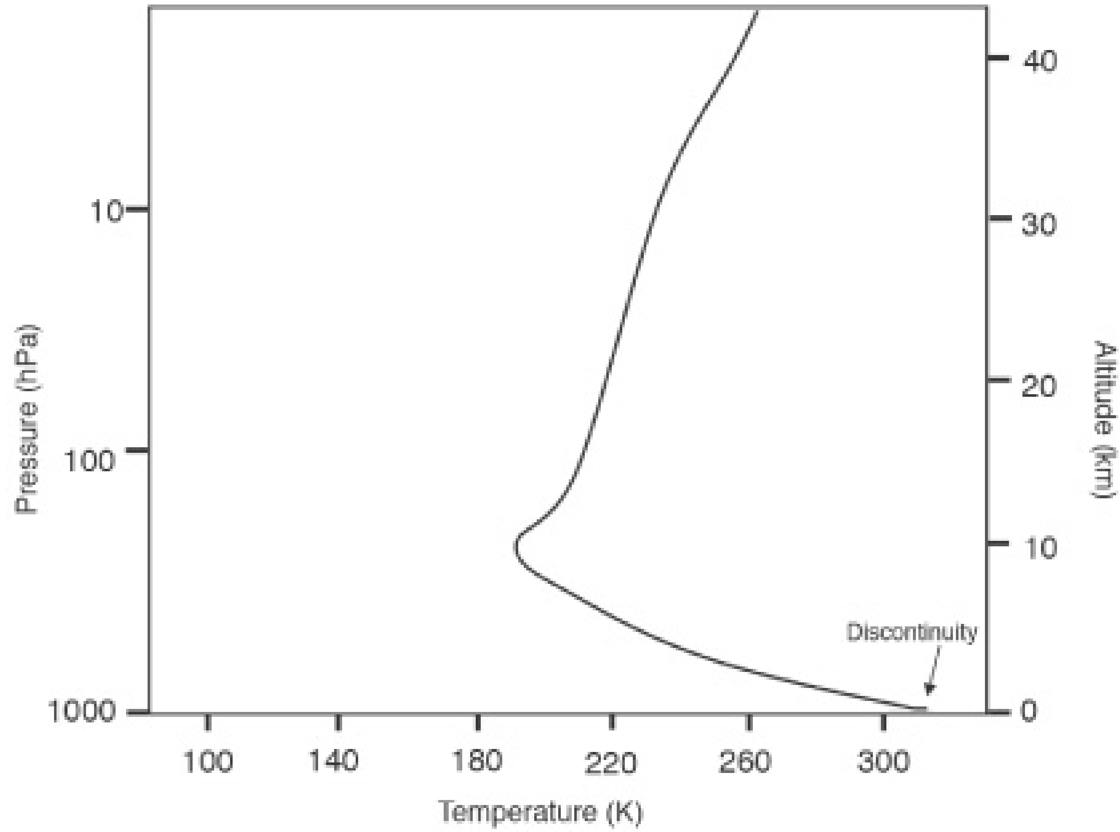


Figure 2.11: The radiative equilibrium profile of the atmosphere obtained by carrying out the calculation schematized in Fig. 2.10. The absorbers are H_2O, O_3, and CO_2. The effects of both terrestrial radiation and solar radiation are included. Note the discontinuity at the surface.

Marshall and Plumb

(Modified from Wells (1997).)

Another Look at T_e and T_S

Recall:

Planet	Albedo	T_e (calculated)	T_e (measured)	Surface Temperature
Mercury	0.058	442	442	442
Venus	0.77	227	230	700
Earth	0.30	256	250	288
Mars	0.15	216	220	210
Jupiter	0.58	98	130	160

Mars T_e and $T_{surface}$

From Radiation and Climate by Vardavas & Taylor, OUP, 2007:

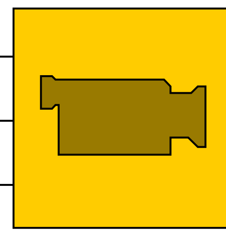
- $A = 0.25$, $F_{sun} = 593$ W/m^2
- Effective $T_e = 210$ K
- Observed $T_s = 218$ K
- Small greenhouse effect of 8 K
- This can increase 5-10 times under very dusty conditions

From Encyclopedia of Planetary Sciences, Springer, 1997:

- $A = 0.26$, $F_{sun} = 590$ W/m^2
- Effective $T_e = 210$ K
- Observed $T_s = 215$ K (but highly variable, 170 K to 275 K)
- Small greenhouse effect of 5 K

Terrestrial Fluxes

- We now want to consider the radiative transfer of flux density in the atmosphere.
- But the terrestrial FLUX DENSITY is not the INTENSITY!
  - → *Schwarzchild's Equation applies to intensity, NOT to flux density.*



Two-Stream Model Solution