Atmospheric Radiation and the Greenhouse Effect

SEA2004F

Week 4 Lecture 5

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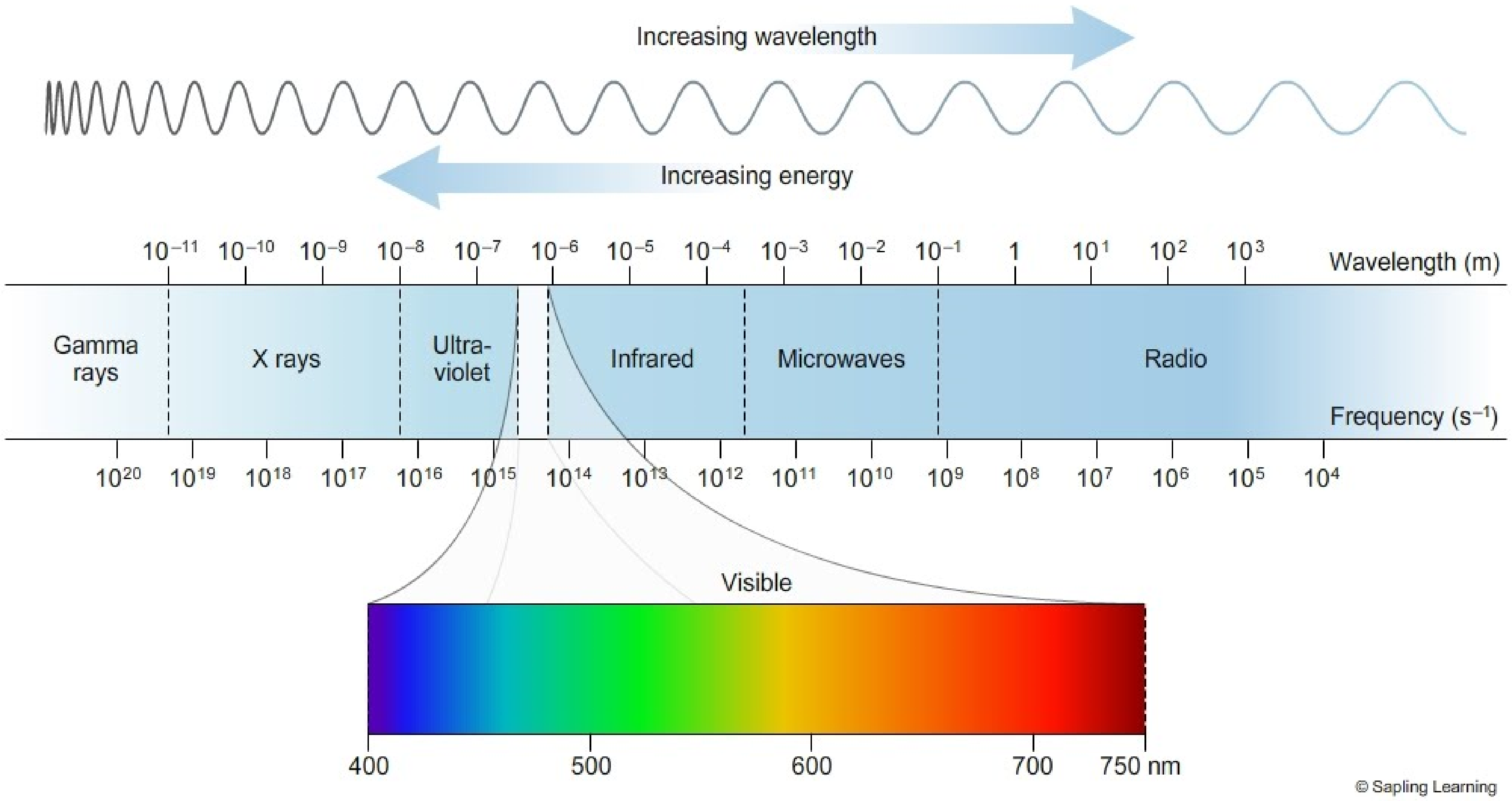
Radiation

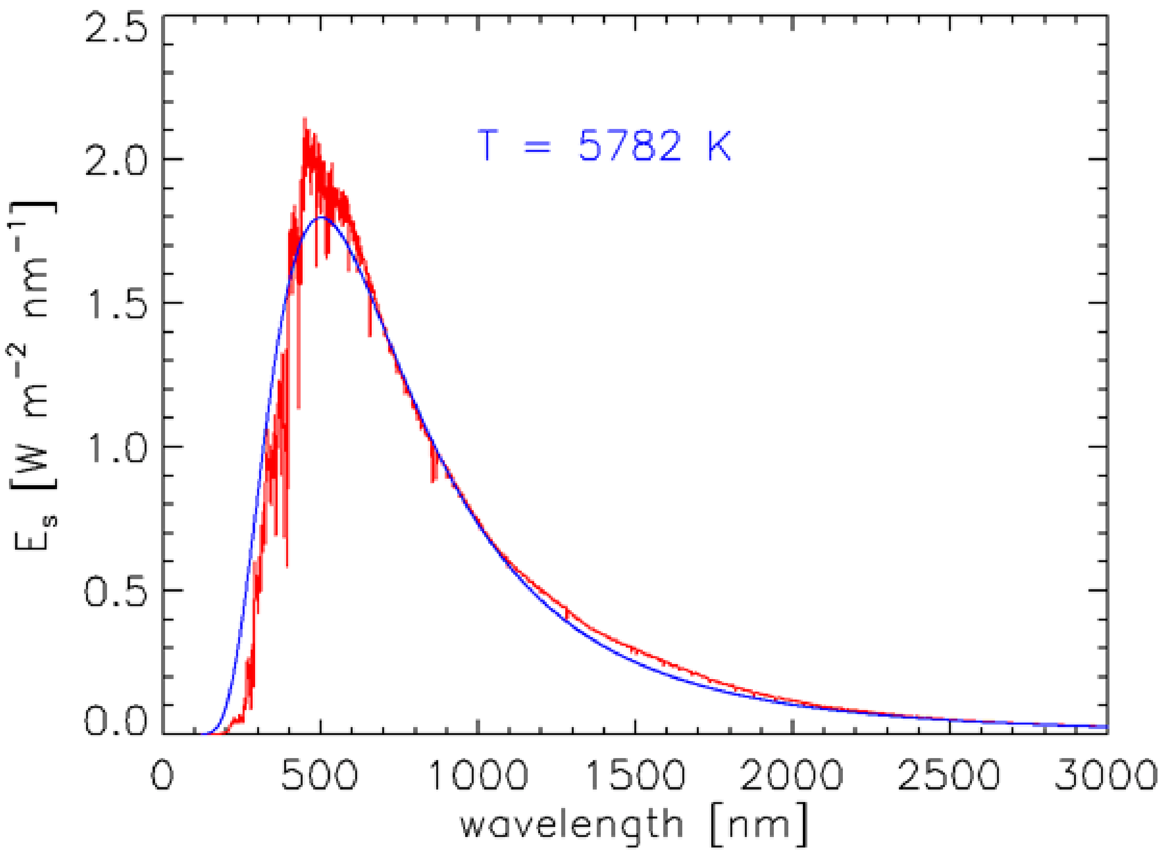
- Energy transmitted by electromagnetic waves
- All objects emit radiation
- An object can emit radiation at a certain wavelength only if it absorbs radiation at that same wavelength

Electromagnetic Spectrum



Sun as a blackbody

- Sun radiates over entire EMS, most concentrated near the visible
- At a given temperature, there is a maximum amount of radiant energy that can be emitted per unit time per unit area of a body
- A "blackbody" is a body that radiates the maximum possible intensity of radiation at every wavelength at a given temperature



Properties of blackbody emitters

- Blackbodies emit radiation at all wavelengths
- Blackbody emissions peak at a wavelength inversely proportional to temperature
- Total radiation flux emitted by a blackbody simplifies to

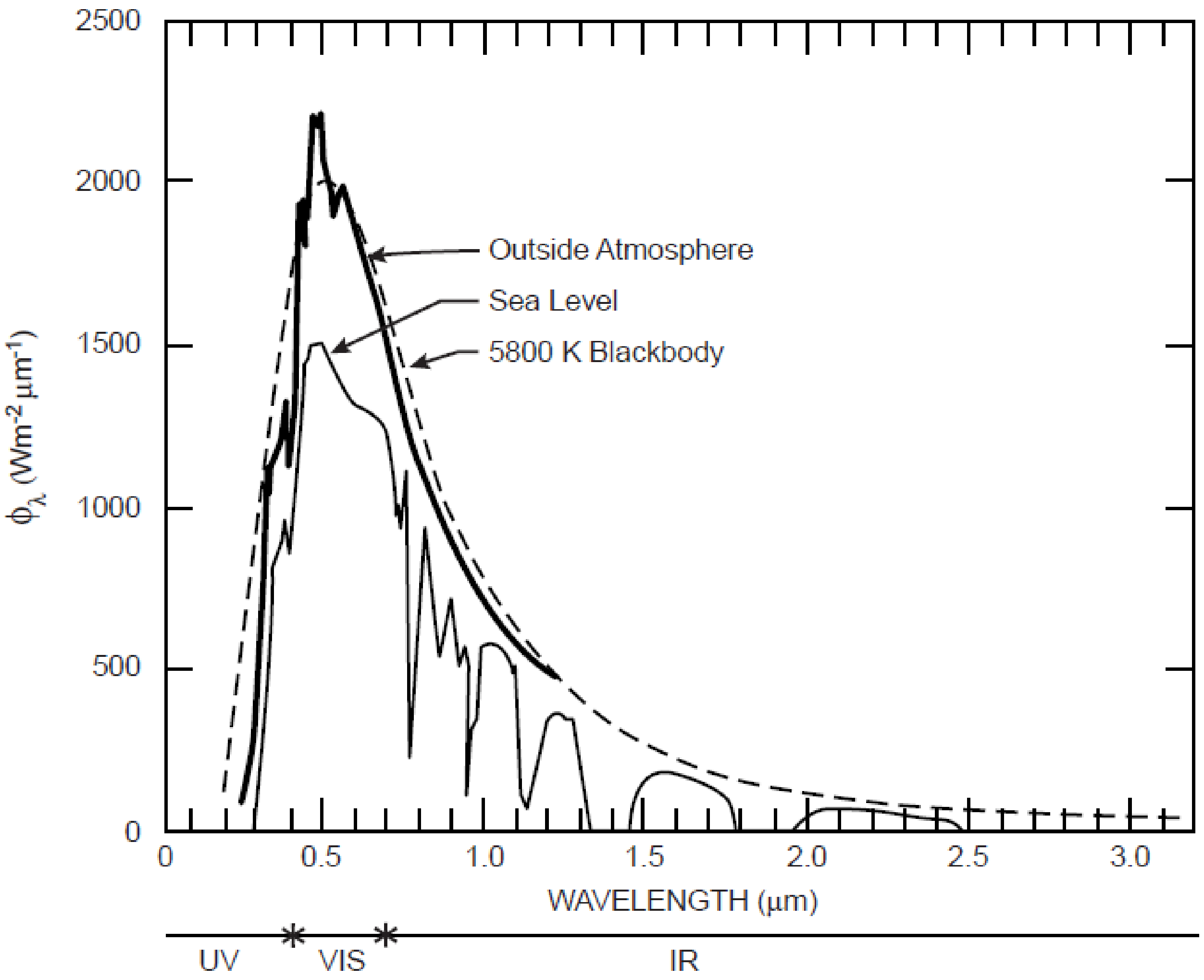
$$\varphi = \sigma T^4$$

where sigma = 5.67×10^{-8} W m^{-2} K^{-4} is the *Stefan-Boltzmann constant*

and T is the temperature of the body in Kelvin

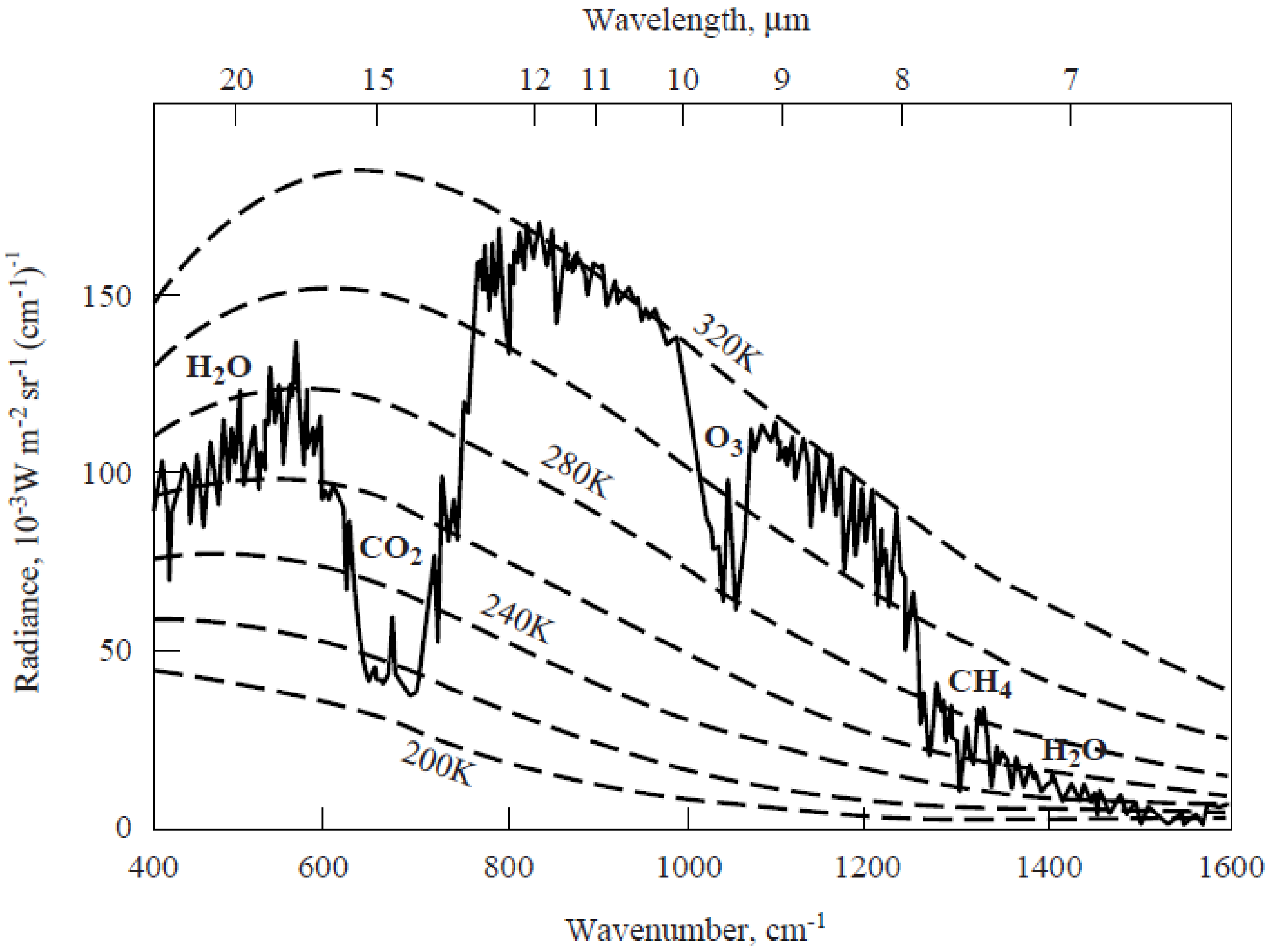
Solar emission spectrum

- Solar radiation spectra measured from a satellite outside Earth's atmosphere and at sea level
- Solar radiation peaks in the visible range of wavelengths
- Maximum in the green
- Weaker at sea level due to reflection by clouds
- Major absorption bands – what are they from?



Terrestrial emission spectrum

- Satellite view over North Africa under clear-sky conditions at noon
- Earth does not emit at visible range – it's not hot enough – otherwise nights wouldn't be dark!
- Blackbody curves for different temps are included for comparison



Radiative balance of the Earth

- Earth must be in energetic equilibrium between the radiation it receives from the sun and the radiation it emits out to space
- Total radiation emitted by the sun is E_{sun} per unit time – assuming T_{sun}=5800 K – is the radiation flux * area of the sun

$$E_s = 4\pi R_S^2 \sigma T_S^4$$

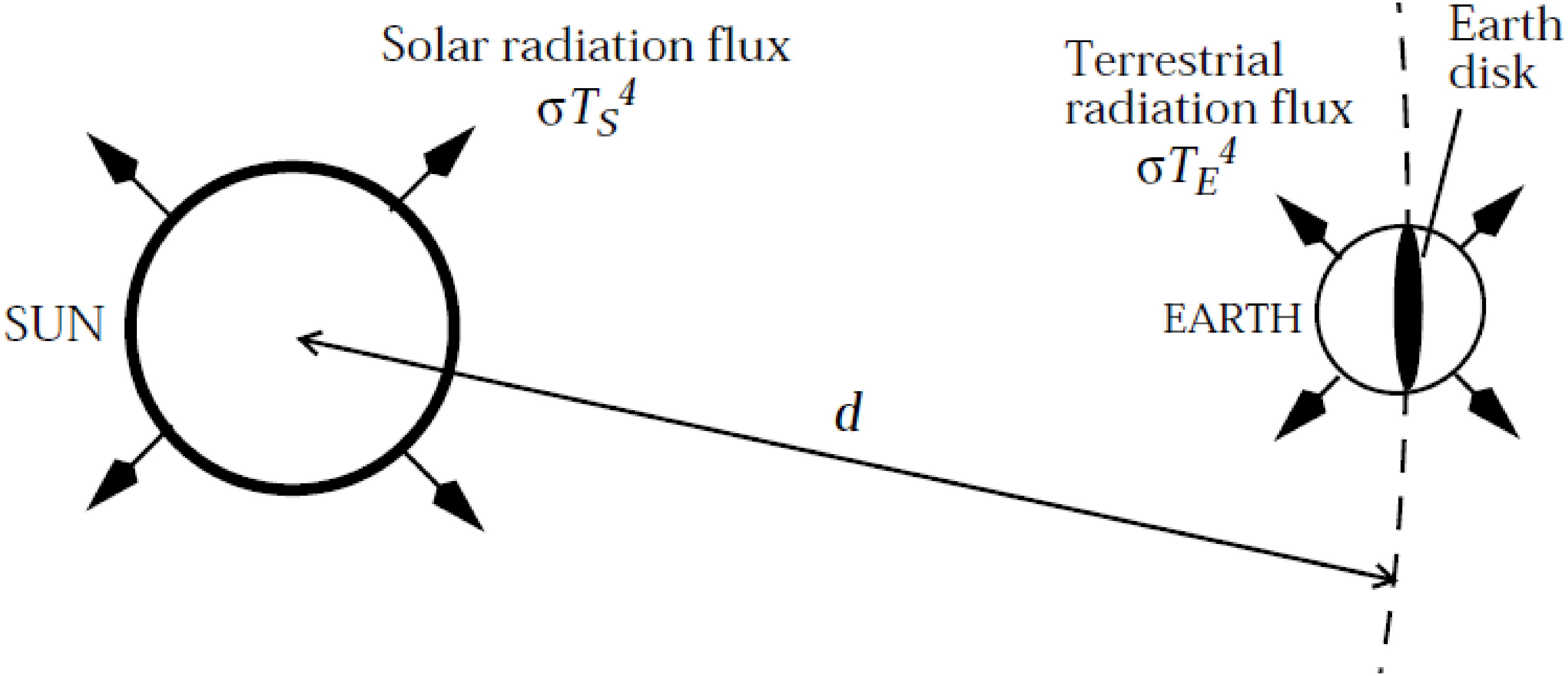
where $R_S=7\text{x}10^5$ km is the Sun's radius.

But – the Earth is at a distance from the Sun. What's the solar radiation flux across that distance?

Radiative balance of the Earth

Earth is 1.5×10^8 km from the Sun

Solar radiation flux (F_s) at that distance is distributed uniformly over the sphere centered at the Sun and of radius d



Radiative balance of the Earth

- Remember – we calculated E_s already

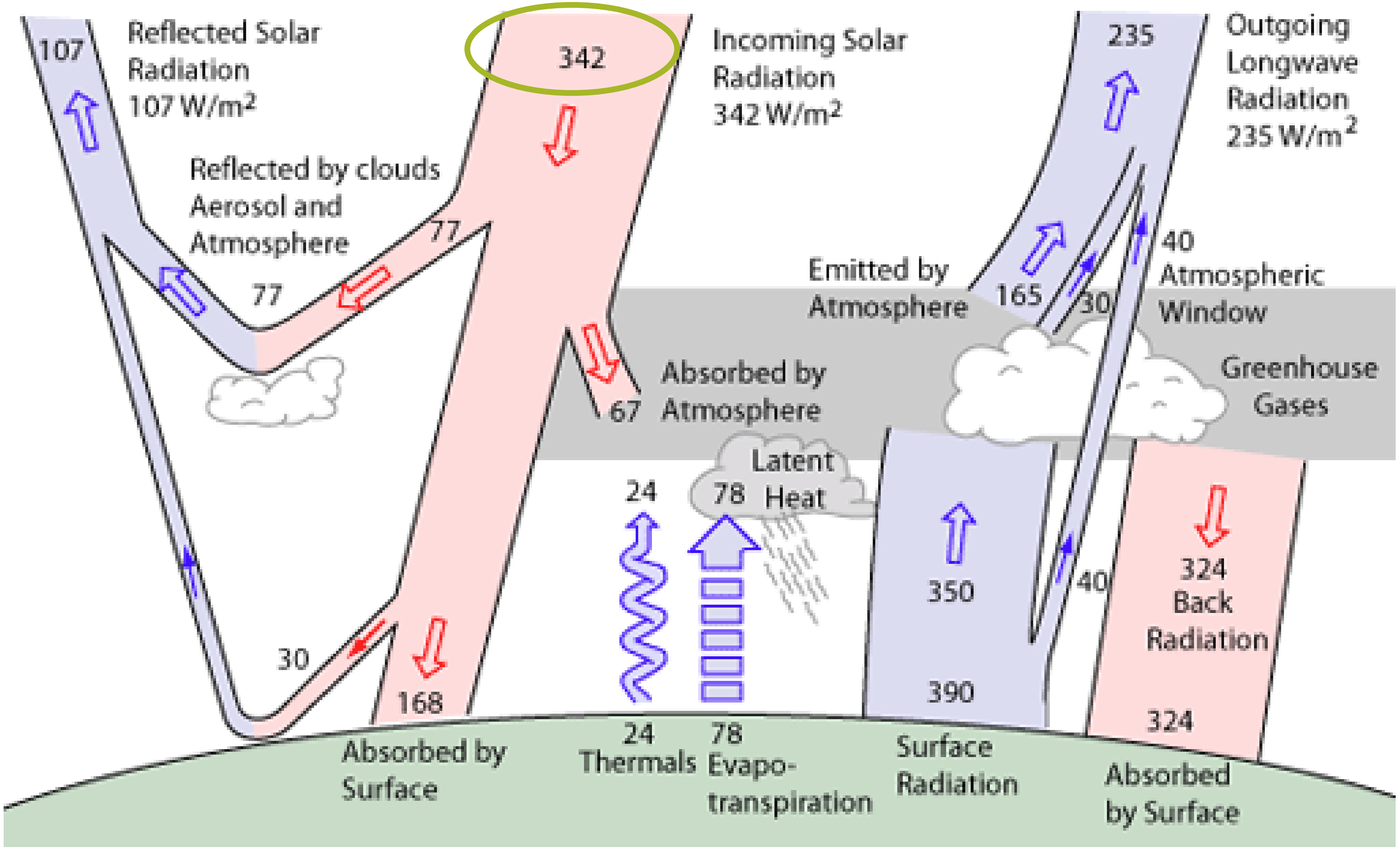
$$F_S = \frac{E_S}{4\pi d^2} = \frac{\sigma T_S^4 R_S^2}{d^2}$$

F_S =1370 W m^{-2}

F_S is the *solar constant* for the Earth. Given data on the distance of other planets from the Sun, one could calculate solar constants for other planets.

The fraction of the solar radiation flux received per unit area of the Earth is ¼ of the solar constant → 342 W m^{-2}

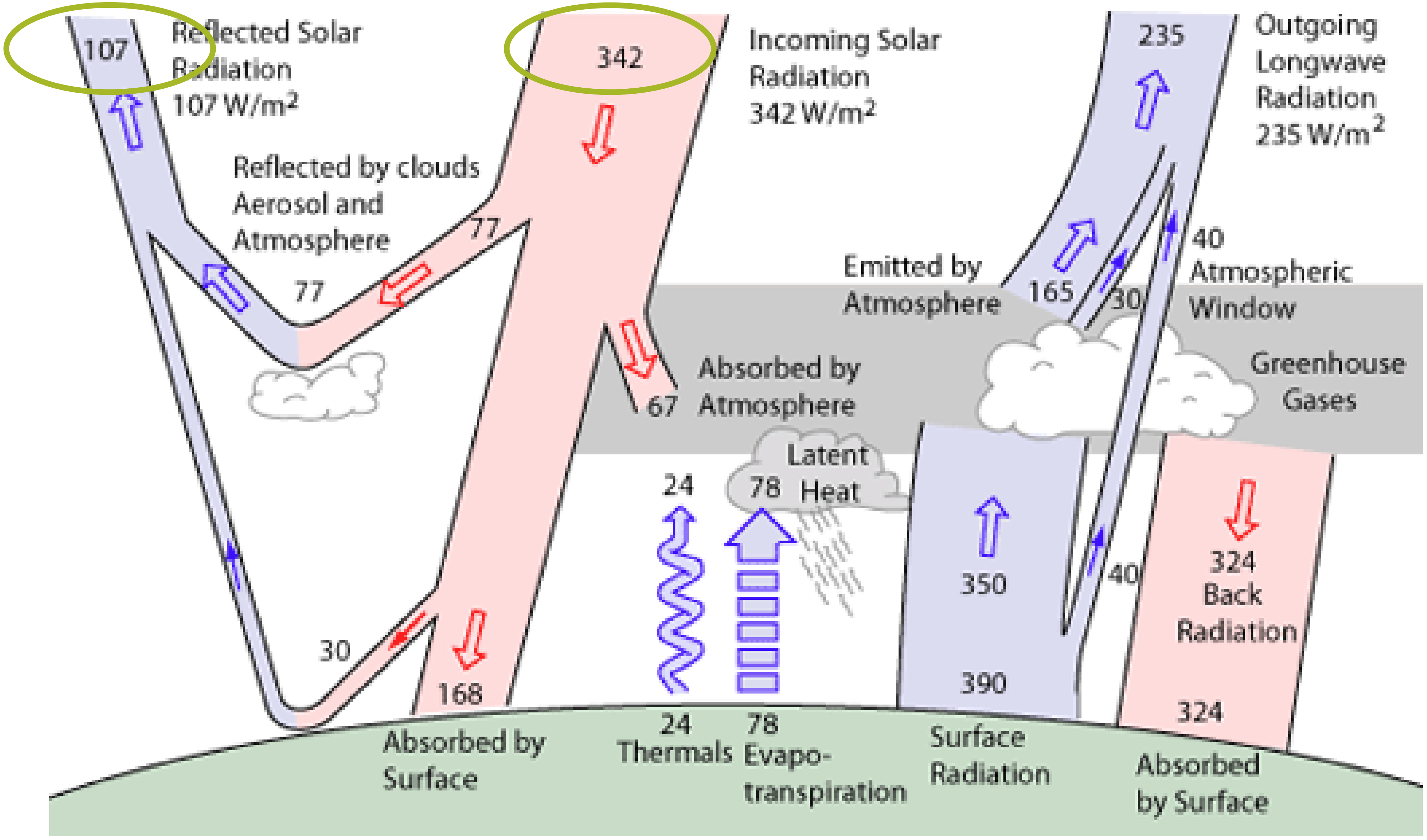
Earth's annual global mean energy balance



What happens to the radiation that gets to Earth?

- A fraction of the radiation is reflected back to space by clouds, snow, and ice, this is the planetary albedo (A)
- Planetary albedo (A) is measured by satellite and is ~ 0.30 for the Earth
- The mean solar radiation flux absorbed per unit area of the Earth's surface = $\frac{F_S(1-A)}{4}$

Earth's annual global mean energy balance



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- The mean solar radiation flux absorbed per unit area of the Earth's surface = $\frac{F_S(1-A)}{4}$
- This absorbed energy must be balanced by emission of terrestrial radiation out to space

$$\frac{F_S(1-A)}{4} = \sigma T_E^4$$

Effective temperature of the Earth

$$T_E = \left[\frac{F_S(1-A)}{4\sigma}\right]^{1/4}$$

Units and Conversions

SI unit of temperature → *Kelvin* (K)

Other units = *Celsius* (°C), *Fahrenheit* (°F) *note no degree symbol in K

°C = K - 273.15

Effective temperature of the Earth

$$T_E = \left[\frac{F_S(1-A)}{4\sigma}\right]^{1/4}$$

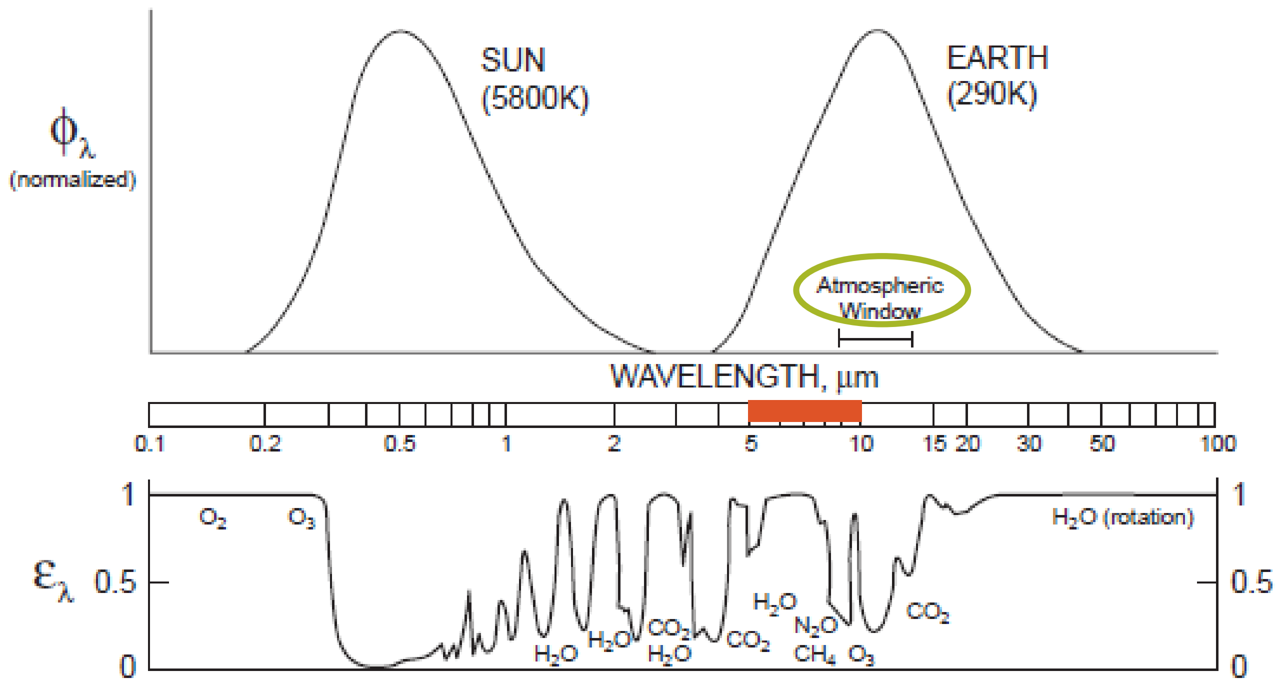
T_E = 255 K = -18.2°C

Does that seem right?

Average surface temperature of the Earth is much higher.
Why?

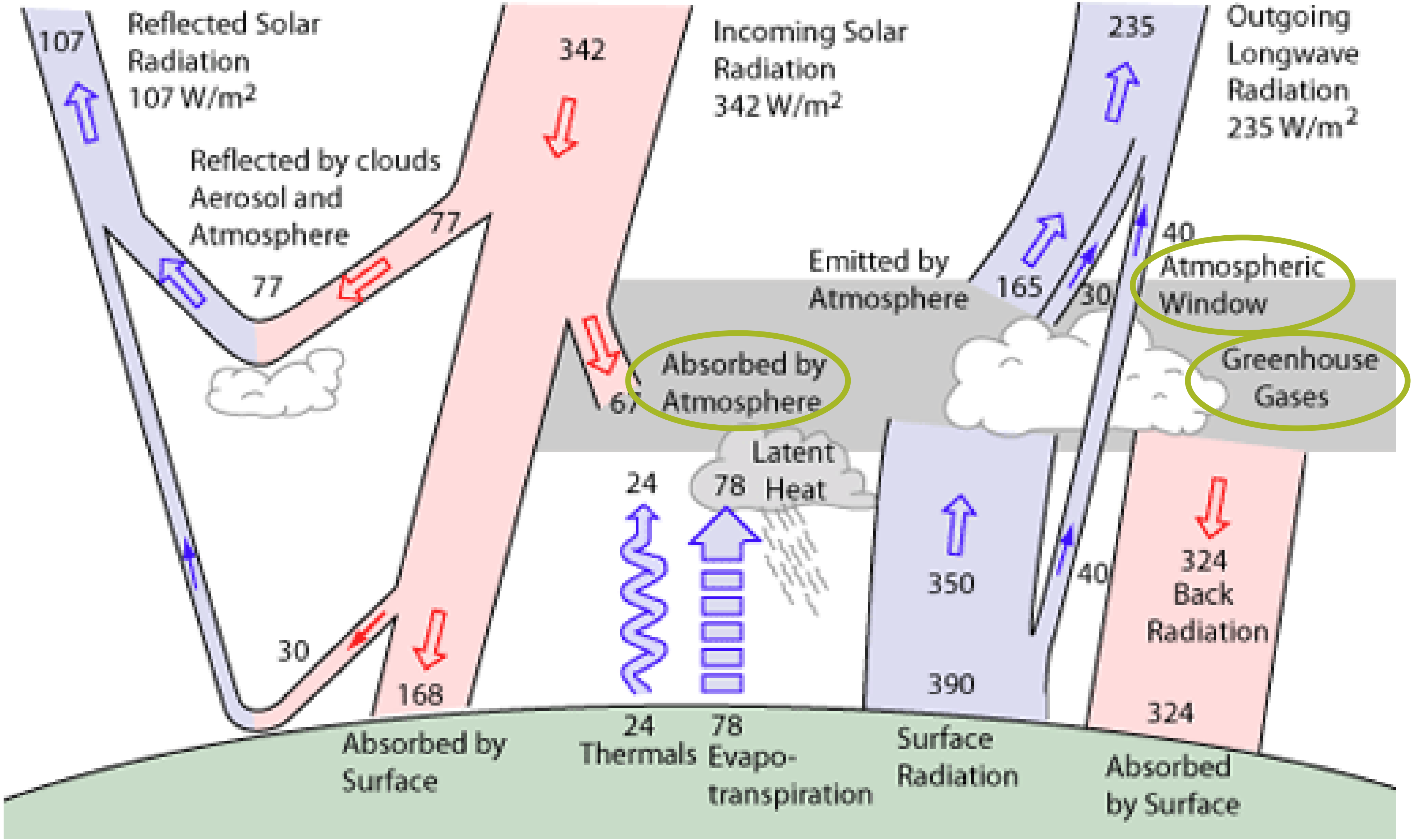
Absorption of radiation by the atmosphere

- A gas molecule absorbs radiation of a given wavelength only if the energy can be used to increase the internal energy of the molecule
- Gases that absorb in the wavelength range of 5-10 µm, where most terrestrial radiation is emitted are called greenhouse gases
- Atmospheric window (8-13 µm) allows direct escape of radiation from the surface of the Earth to space – important for defining the temperature of the Earth's surface



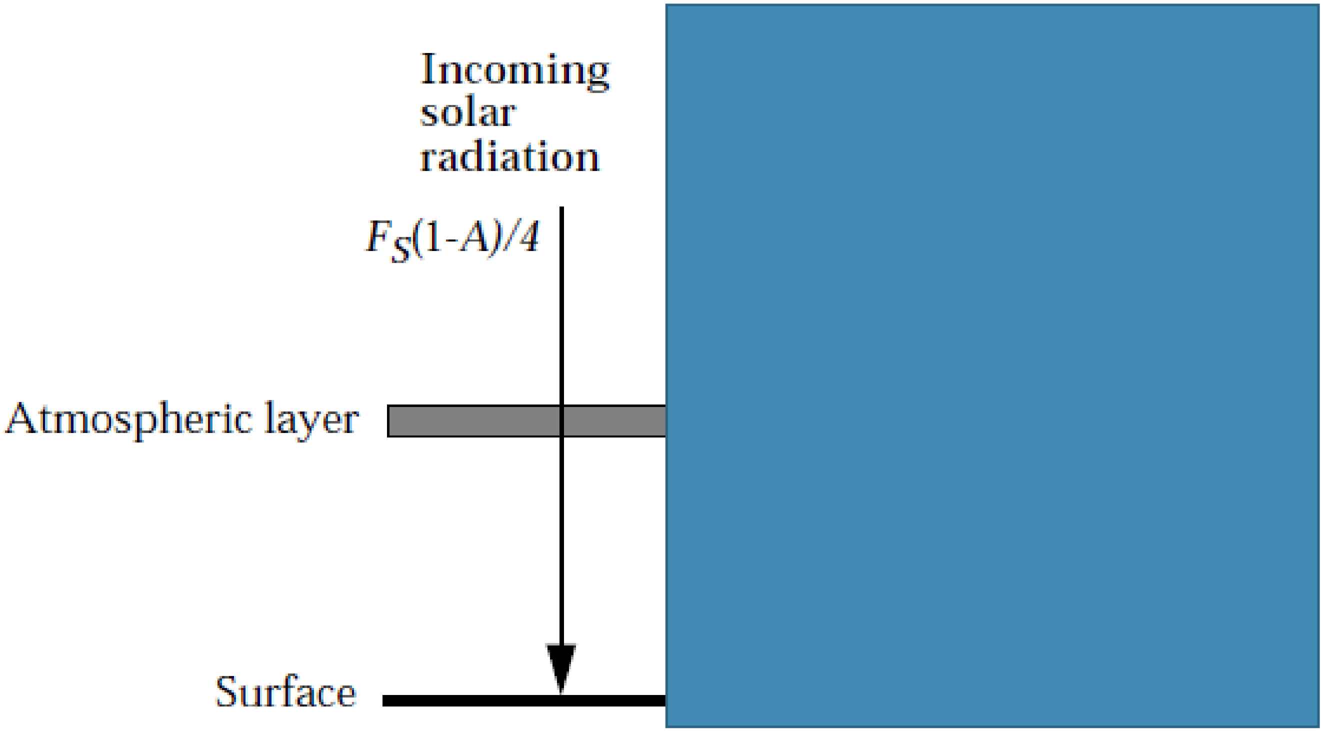
Efficiency of absorption of radiation by the atmosphere as a function of wavelength

Earth’s annual global mean energy balance



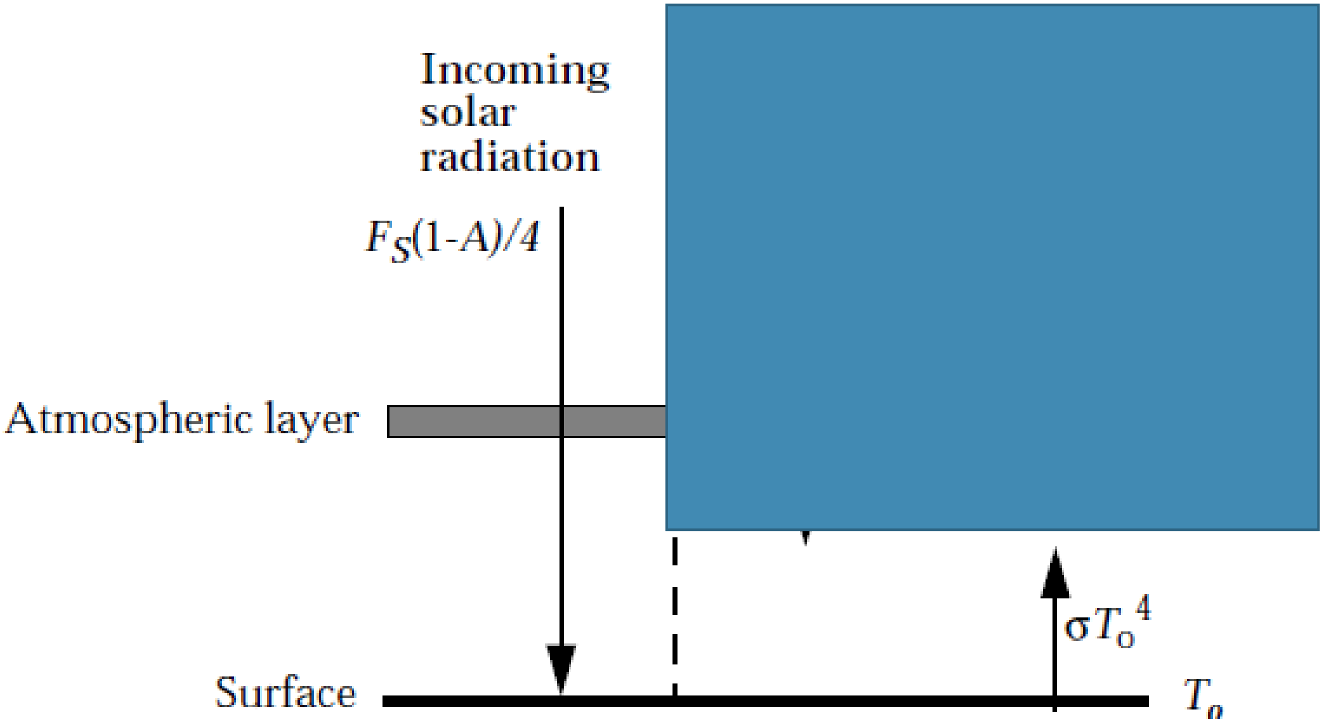
Simple Greenhouse Model

- The atmosphere is idealized as a simple isothermal layer (no temperature variations) – it's placed above the Earth
- The atmospheric layer allows solar radiation through



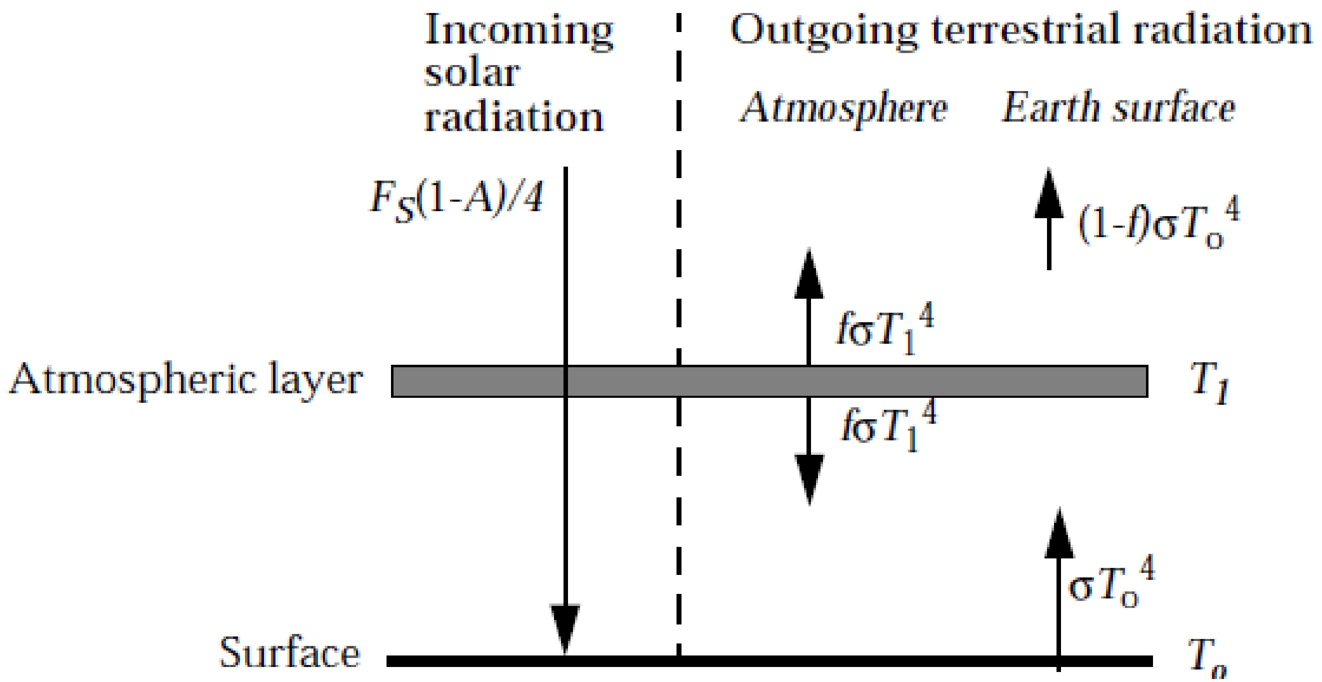
Simple Greenhouse Model

- The atmosphere is idealized as a simple isothermal layer (no temperature variations) – it's placed above the Earth
- The atmospheric layer allows solar radiation through
- Surface of the Earth has a temperature of T_0, and radiates as a blackbody



Simple Greenhouse Model

- The atmospheric layer absorbs a fraction (f) of the terrestrial radiation because of the presence of greenhouse gases
- The atmospheric layer has a temperature of T_1
- Calculate energy balance of the Earth + atmosphere system



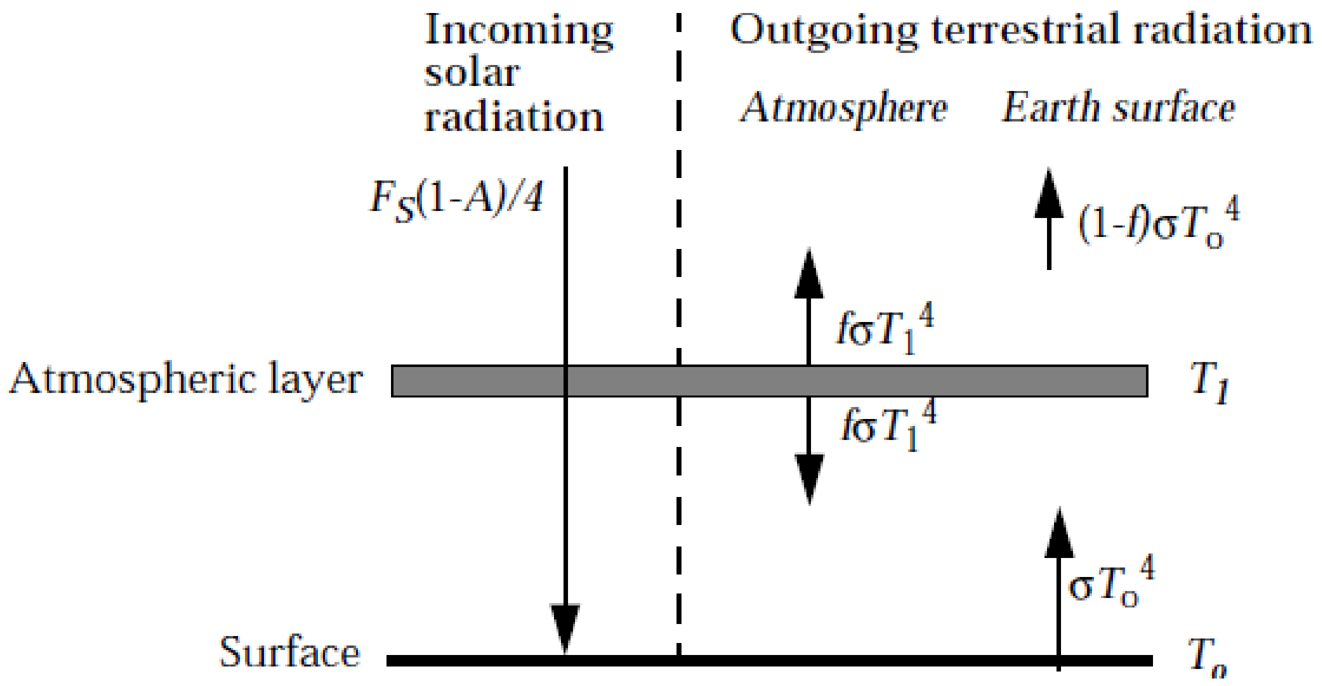
Simple Greenhouse Model

- Calculate energy balance of the Earth + atmosphere system

$$\frac{F_S(1-A)}{4} = (1-f)\sigma T_0^4 + f\sigma T_1^4$$

- Calculate energy balance of atmospheric layer

$$f\sigma T_0^4 = 2f\sigma T_1^4$$

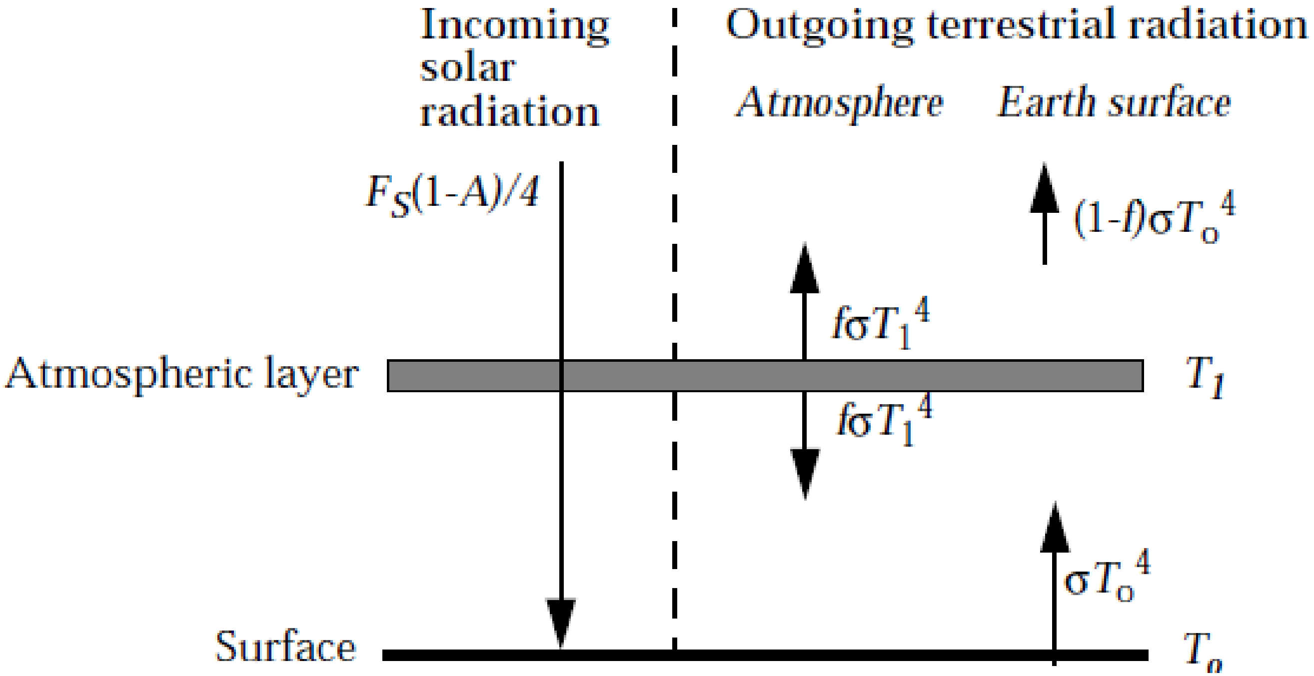


Simple Greenhouse Model

- Substitute and re-arrange

$$T_0 = \left[\frac{F_S(1-A)}{4\sigma(1-\frac{f}{2})}\right]^{1/4}$$

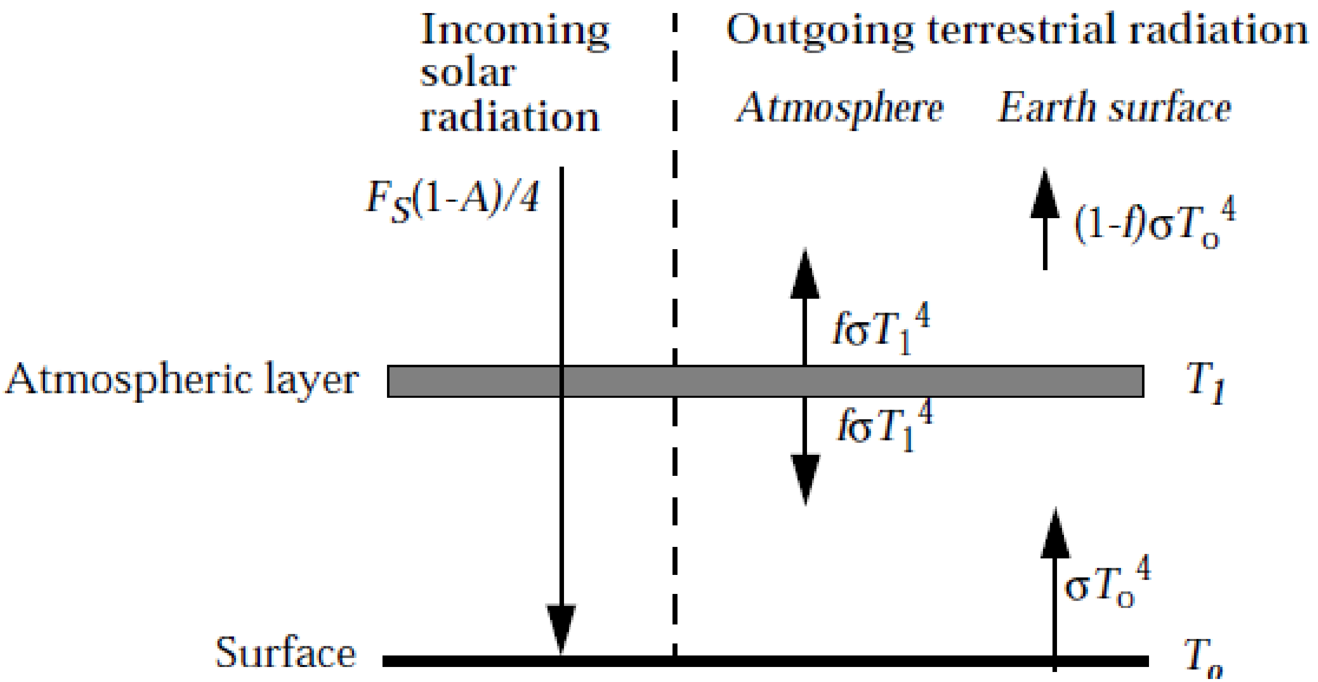
- We know the average surface temperature of the Earth, so can solve for f



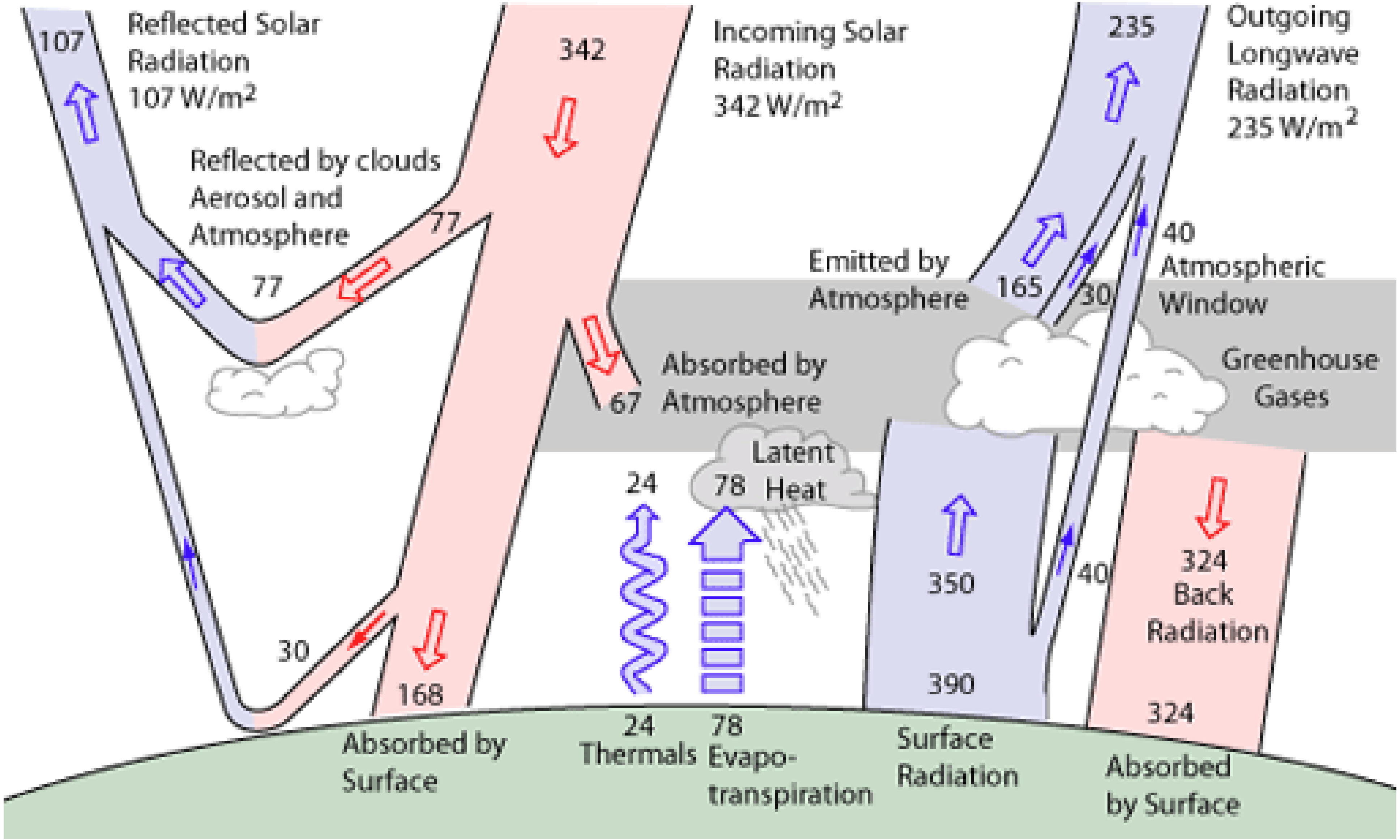
Simple Greenhouse Model

$$T_0 = \left[\frac{F_S(1-A)}{4\sigma(1-\frac{f}{2})}\right]^{1/4}$$

- f = 0.77
- Observed average surface temperature can be reproduced by assuming that the atmospheric layer absorbs 77% of terrestrial radiation
- Increasing concentrations of greenhouse gases increase the absorption efficiency of f of the atmosphere, which will increase T_0

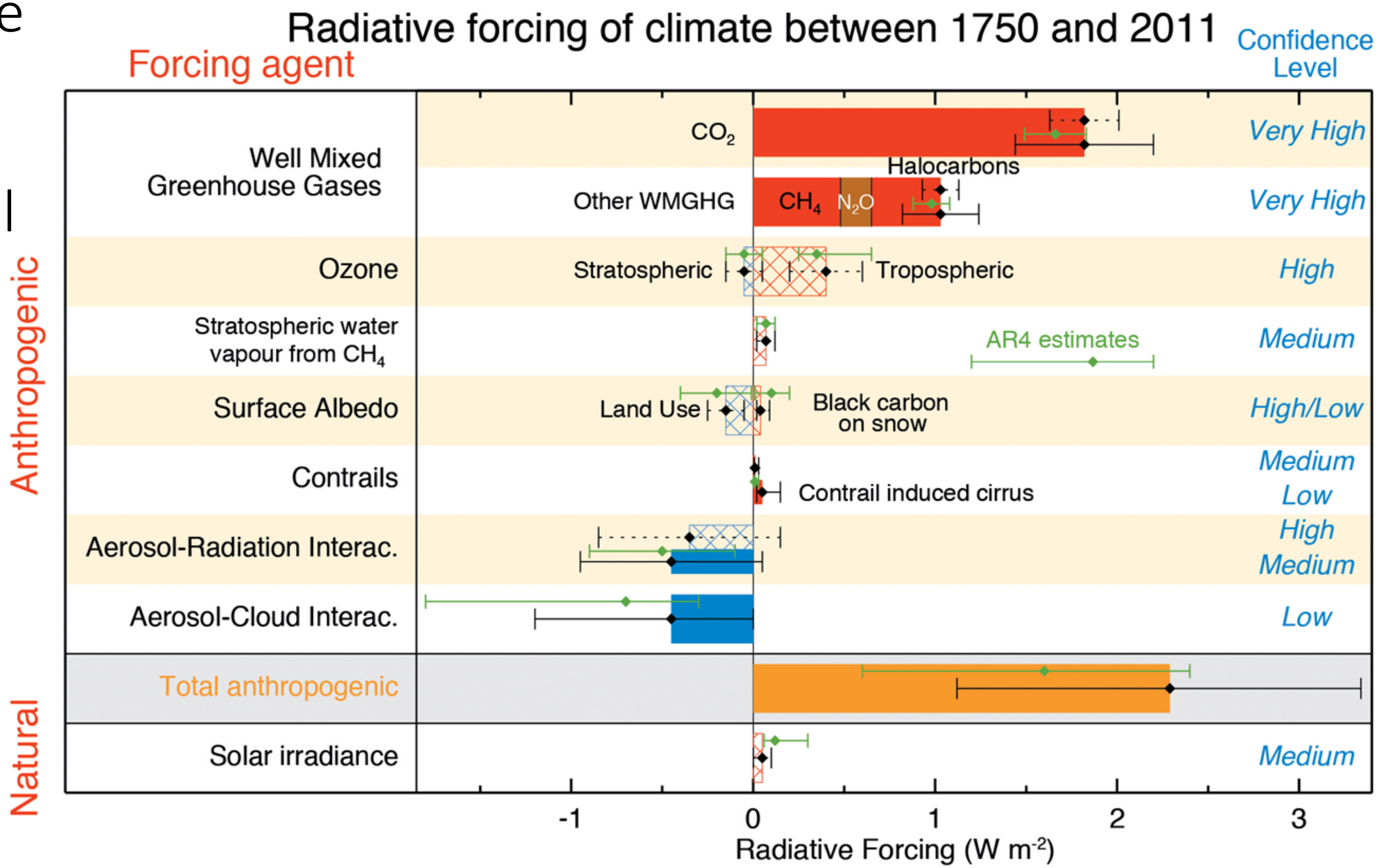


Earth’s annual global mean energy balance



Radiative Forcing

- Radiative forcing is a measure of the net change in the energy balance of the Earth system in response to some external perturbation

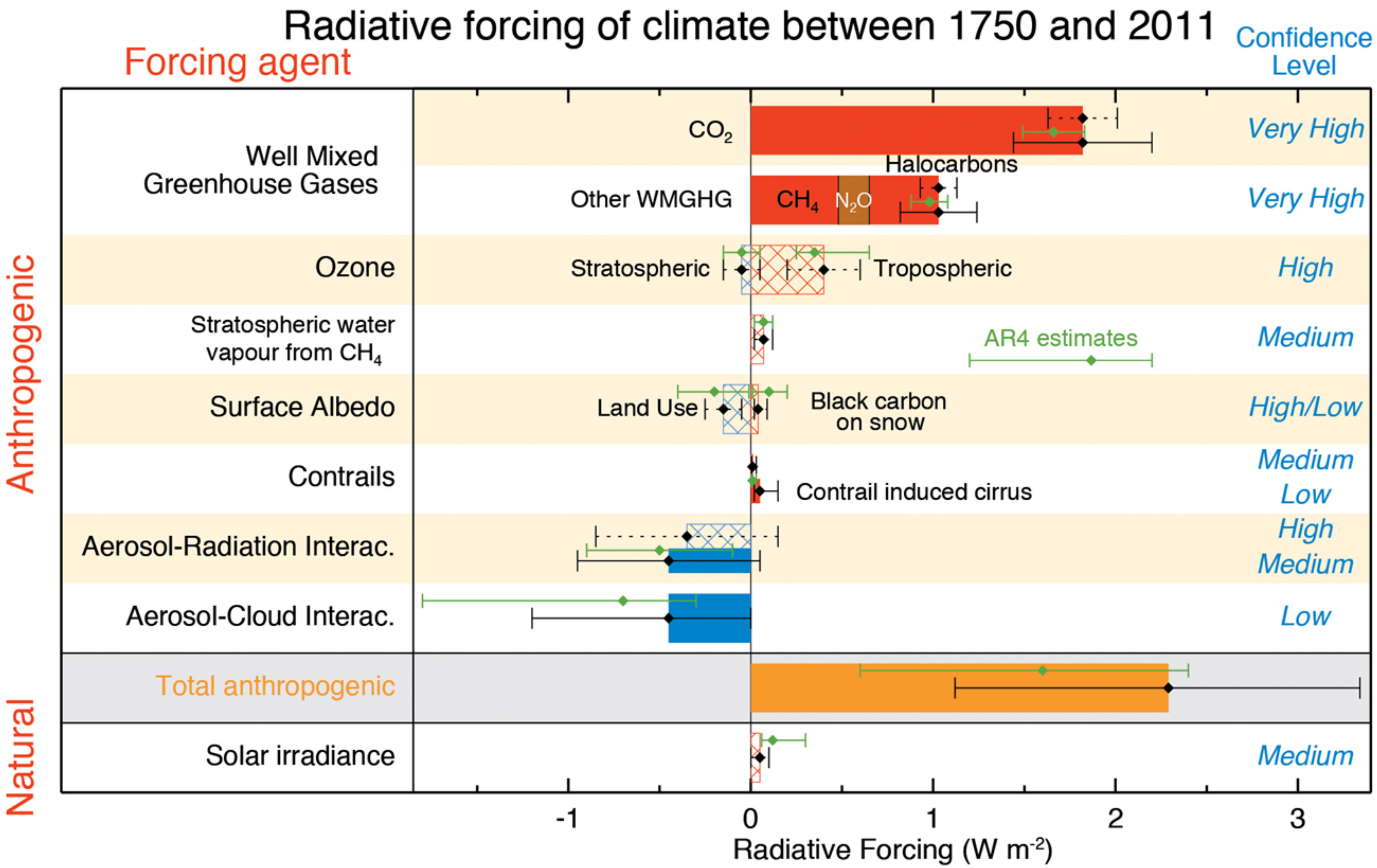


Radiative Forcing

- Not calculated using simple model we developed here
- *General circulation models* (GCMs) resolve the horizontal heterogeneity of the Earth's surface and its atmosphere by solving globally the three-dimensional equations for conservation of energy, mass, and momentum
- In GCMs, a radiative perturbation associated with an increase in a greenhouse gas triggers an initial warming; complex responses follow involving, e.g., enhanced evaporation of water vapor from the ocean, changes in cloud cover, changes in atmospheric and oceanic circulation

Radiative Forcing

- Can quantitatively relate all gases to a reference gas (CO_2) to calculate global warming potential for easy comparison



Global Warming Potential

- Time integrated global mean radiative forcing of a pulse emission of 1 kg of some compound, relative to that of 1 kg of CO_2
- Provides a way to evaluate trade-offs between emissions of different forcing agents
- It accounts for the gases lifetime
- Over a 100 year time horizon, reducing N_2O emissions by 1 kg is as effective from a greenhouse perspective as reducing CO_2 emissions by 289 kg

Table 2.14. *Lifetimes, radiative efficiencies and direct (except for CH_4) GWPs relative to CO_2. For ozone-depleting substances and their replacements, data are taken from IPCC/TEAP (2005) unless otherwise indicated.*

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency ($W\ m^{-2}\ ppb^{-1}$)	Global Warming Potential for Given Time Horizon			
				SAR‡ (100-yr)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See below[a]	[b]1.4×10^{-5}	1	1	1	1
Methane[c]	CH_4	12[c]	3.7×10^{-4}	21	72	25	7.6
Nitrous oxide	N_2O	114	3.03×10^{-3}	310	289	298	153