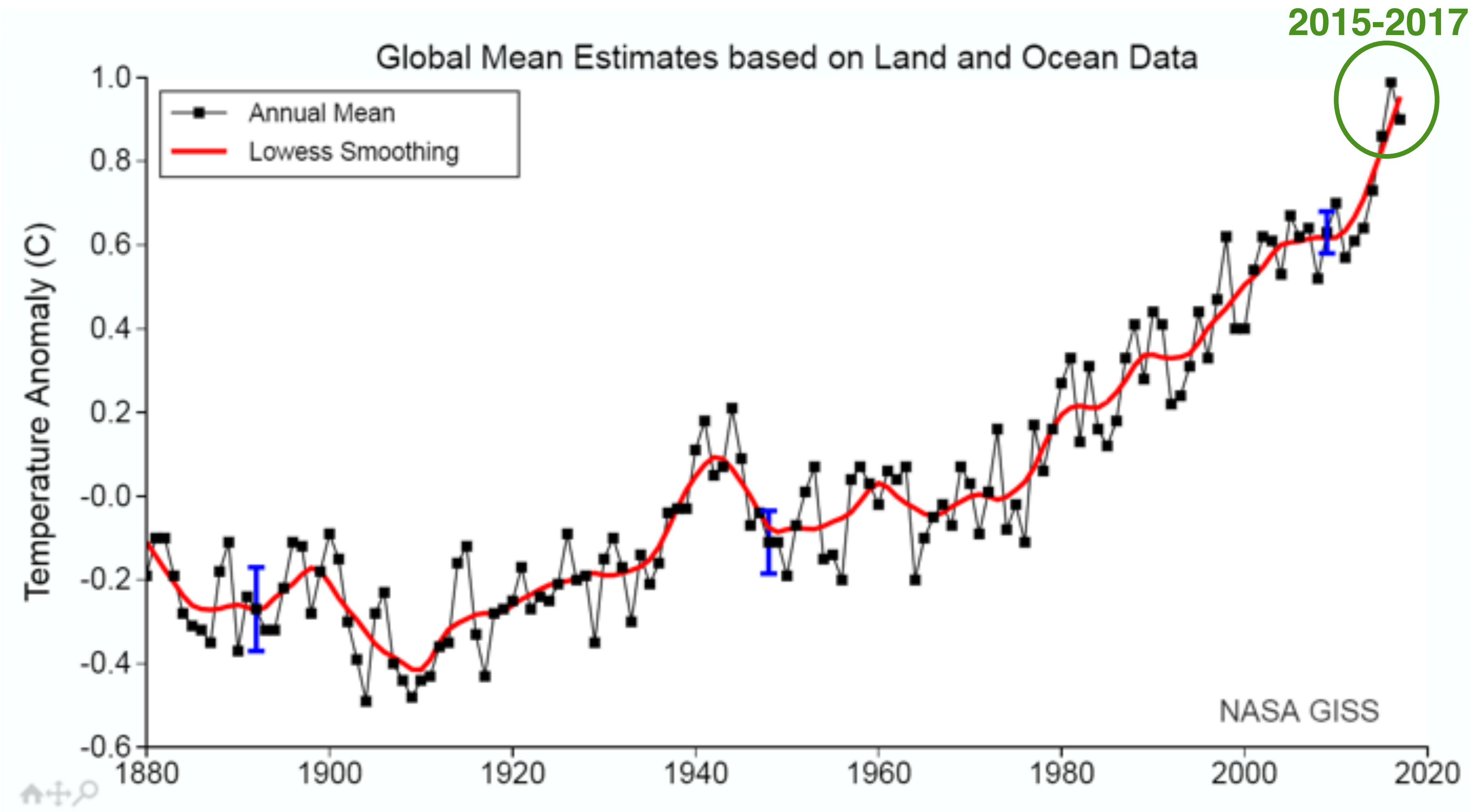
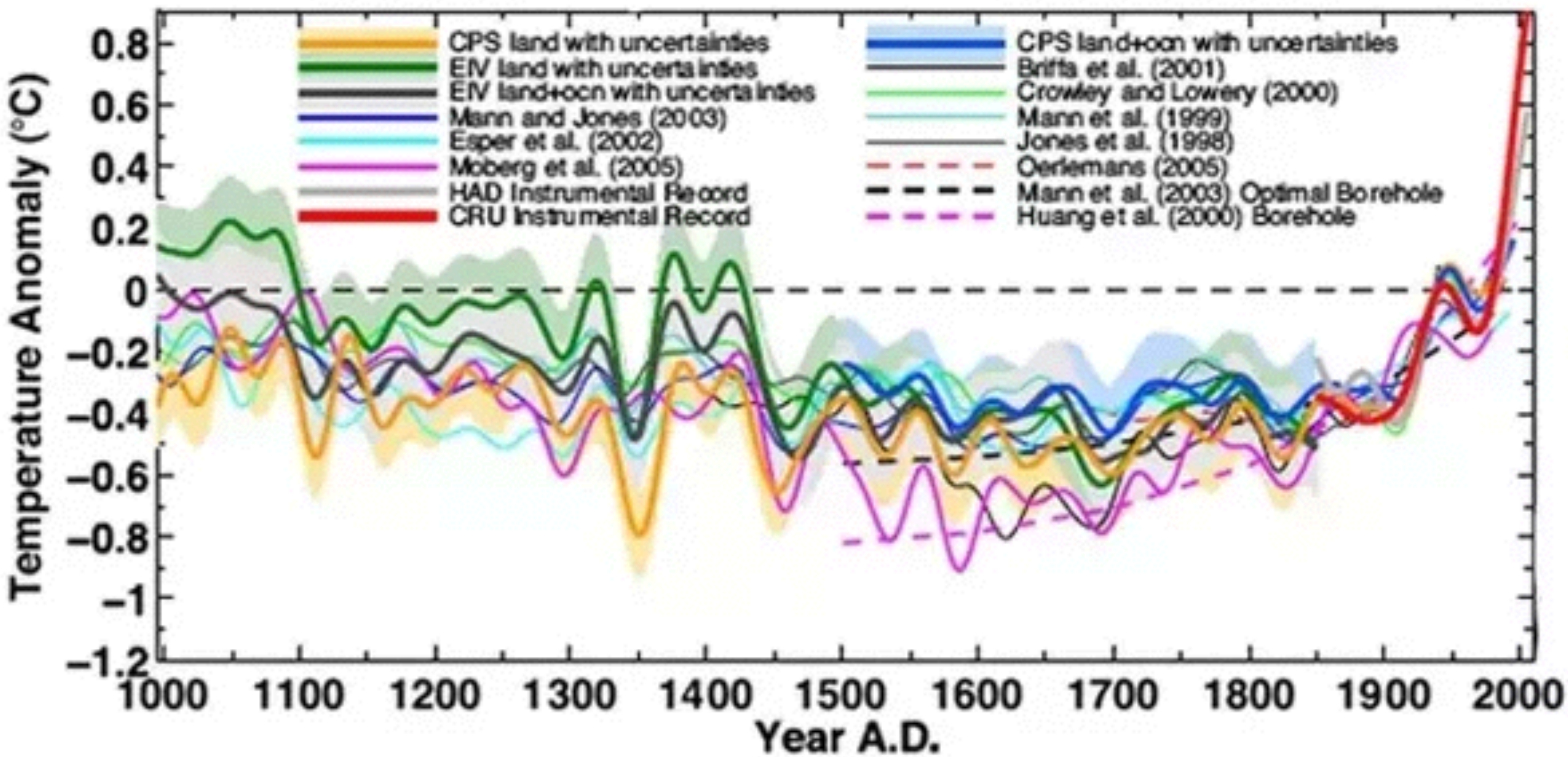
Global surface temperature trend

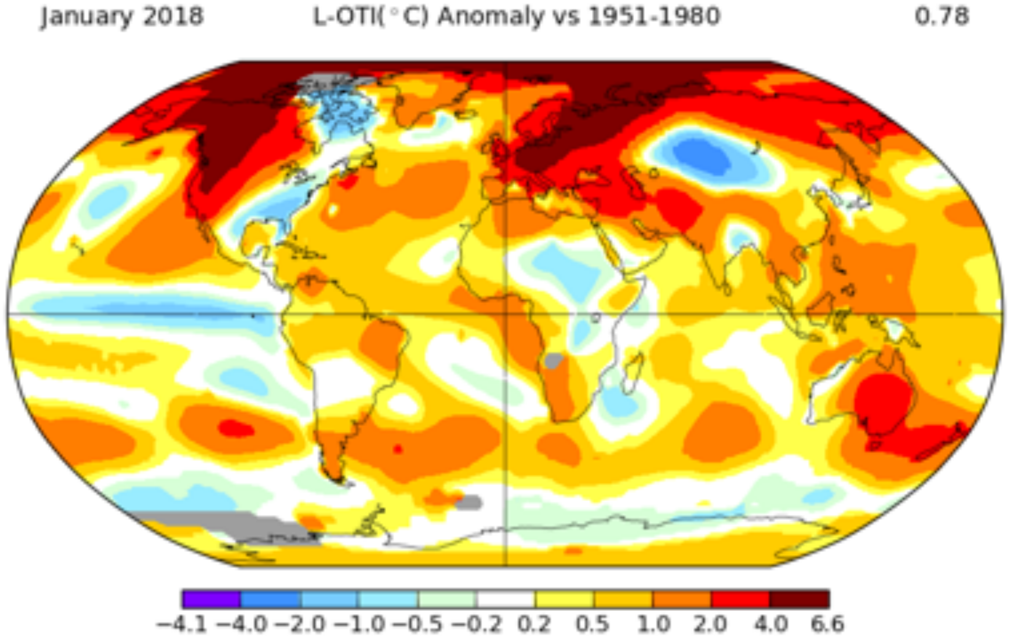


NASA/GISTEMP [2018]

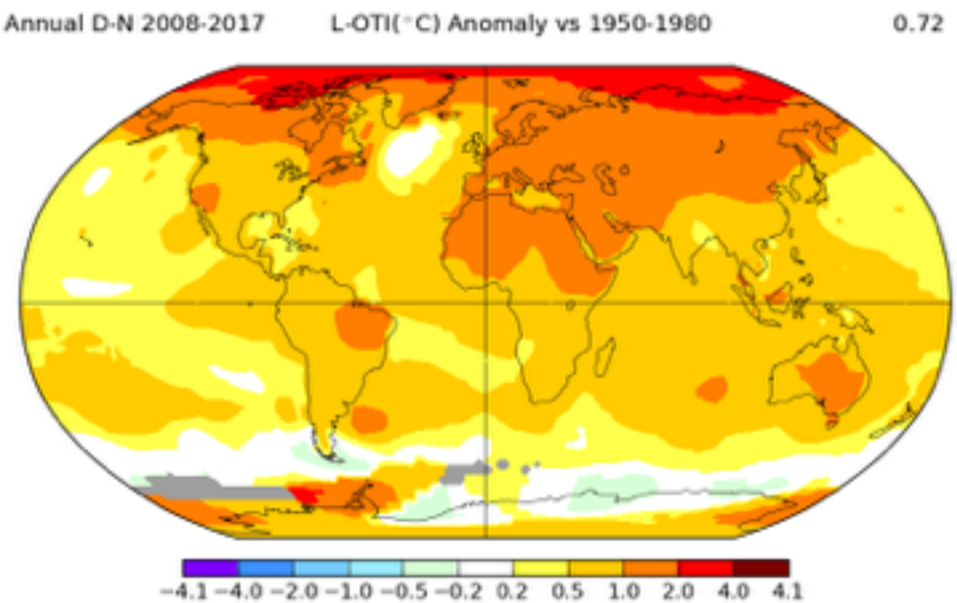
Reconstructed global temperature for past 1,000 years



January 2018 temperature anomaly relative to Jan 1951-1980



Annual 2008-2017 temperature anomaly relative to 1950-1980

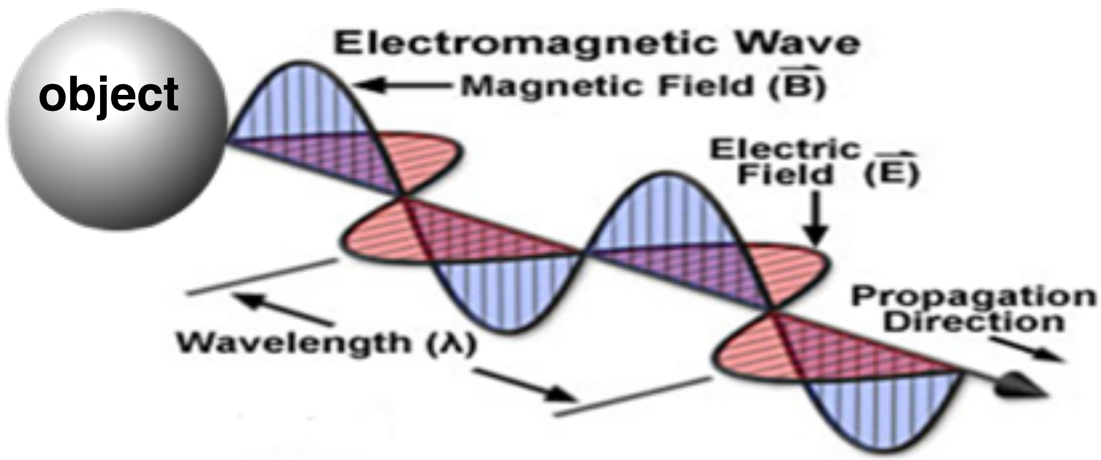


GISTEMP [2017]

Sea ice in Boston Harbor (Boston Globe, Jan 1 2018)

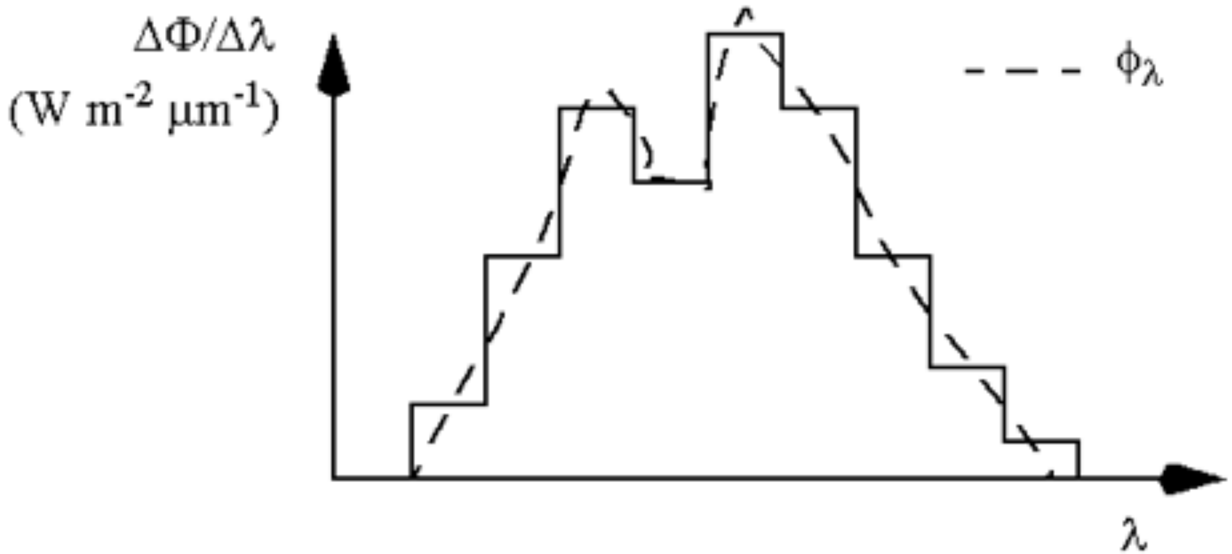
Emission of radiation

- Radiation is energy transmitted by electromagnetic waves
- All objects at $T > 0$ K emit radiation



Radiation spectrum

- One can measure the radiation flux spectrum emitted by a unit surface area of object:



Here $\Delta\Phi$ is the radiation flux emitted in $[\lambda, \lambda+\Delta\lambda]$

$$\phi_\lambda = \lim_{\Delta\lambda \to 0}\left(\frac{\Delta\Phi}{\Delta\lambda}\right)$$ is the flux distribution function characteristic of the object

Total radiation flux emitted by object: $\Phi = \int_0^\infty \phi_\lambda d\lambda$

BLACKBODY RADIATION

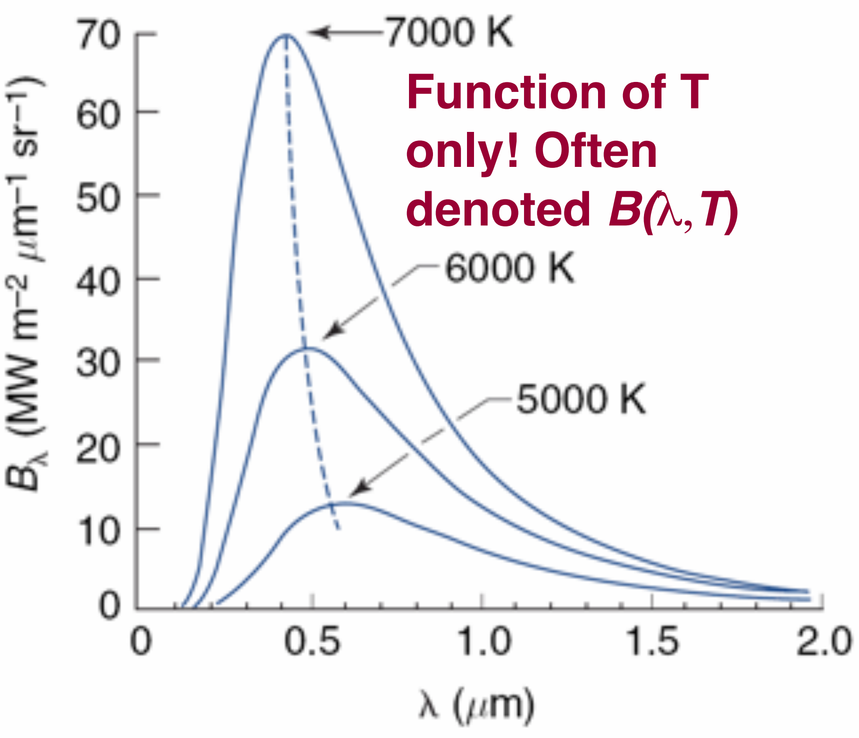
- Objects that absorb 100% of incoming radiation are called **blackbodies**
- For blackbodies, ϕ_λ is given by the **Planck function:**

$$\phi_\lambda^b = \frac{2\pi hc^2}{\lambda^5\left(\exp\left(\frac{hc}{kT\lambda}\right)-1\right)}$$

$$\Phi = \sigma T^4$$

$\sigma = 2\pi^5 k^4/15c^2h^3 =$ **5.67x10^{-8} W m^{-2} K^{-4}**
is the Stefan-Boltzmann constant

$\lambda_{max} = hc/5kT$ **Wien's law**

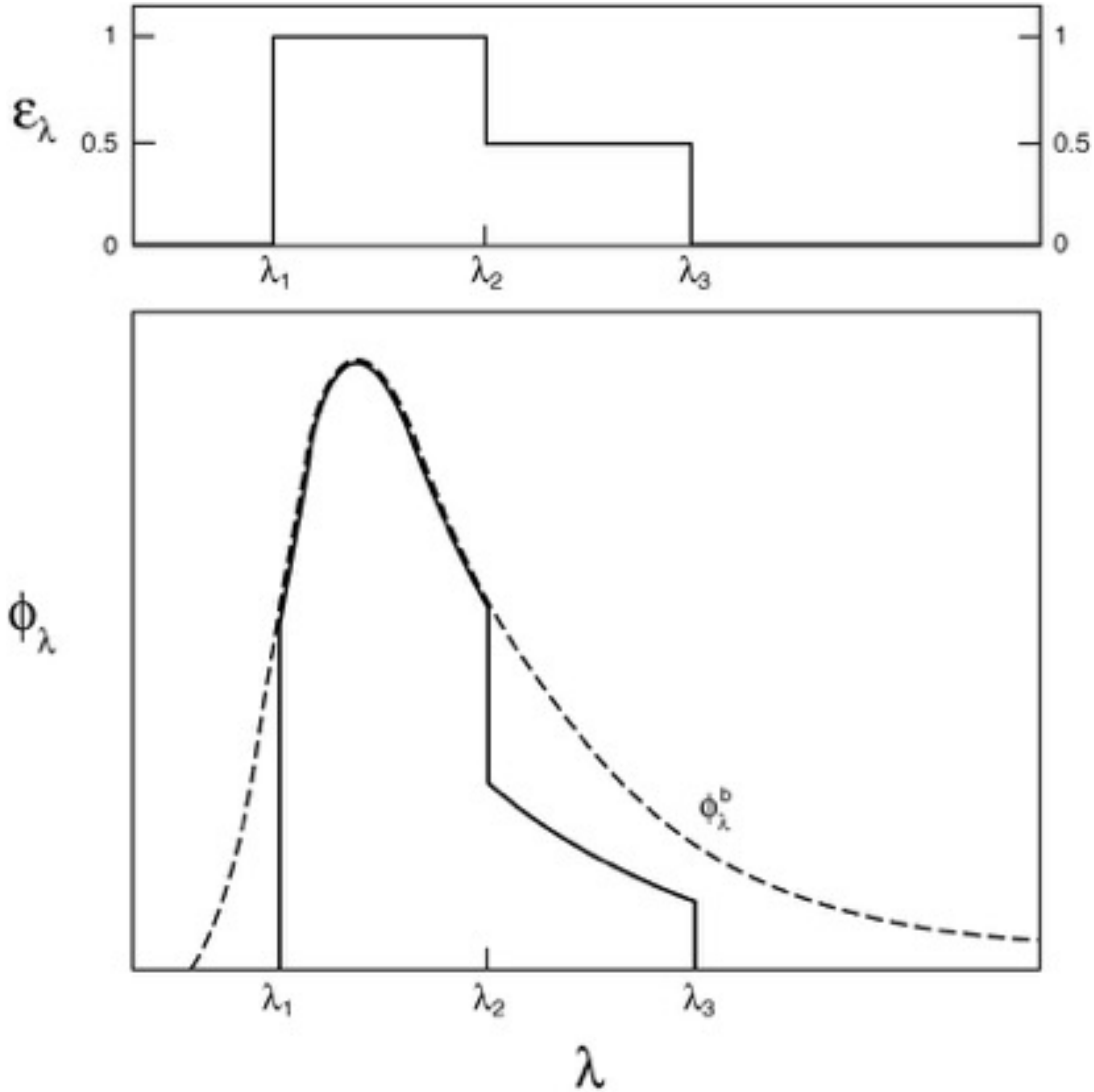


Function of T only! Often denoted $B(\lambda,T)$

KIRCHHOFF'S LAW:
Emissivity $\varepsilon(\lambda, T)$ = Absorptivity

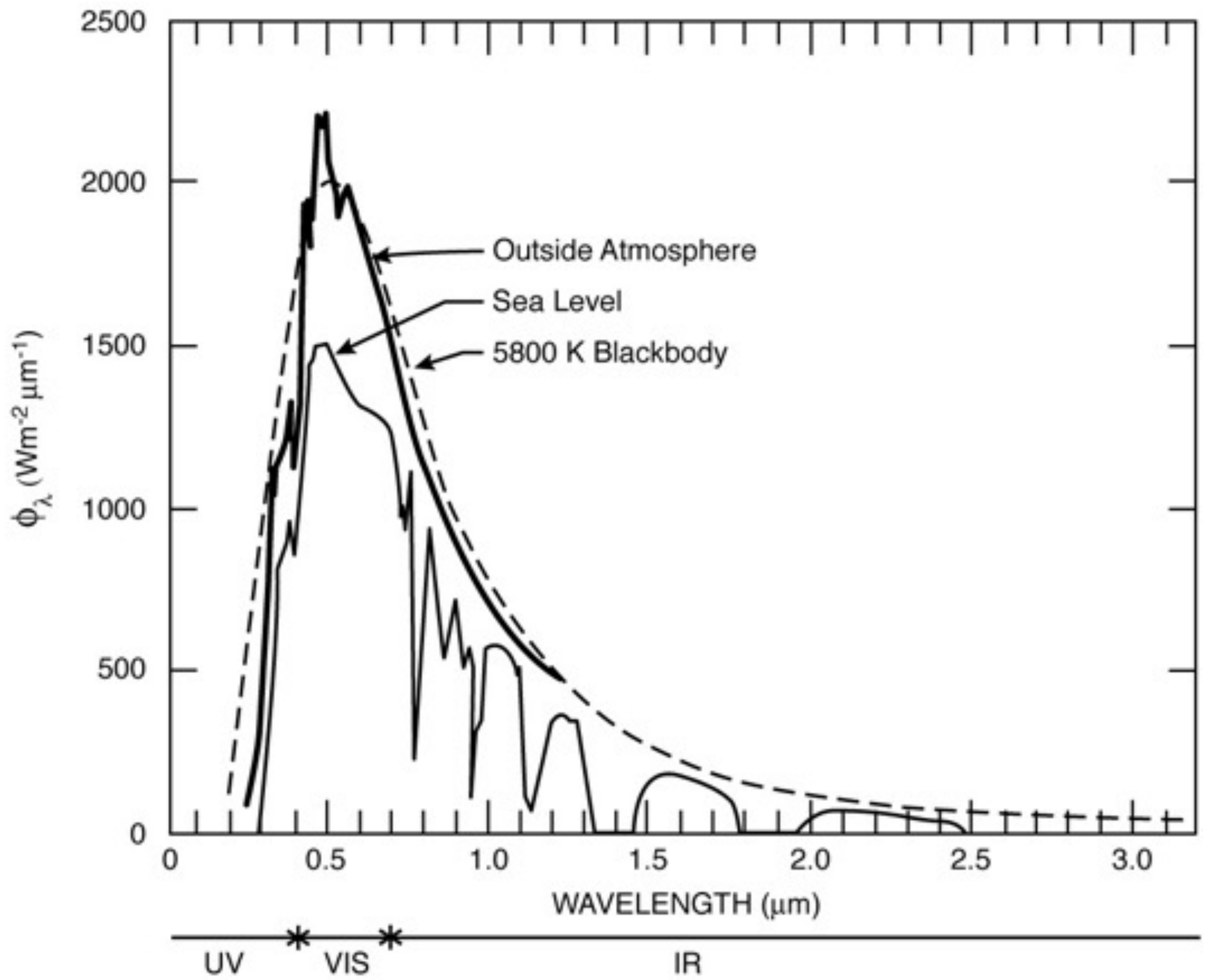
For any object: $\phi_\lambda(T) = \varepsilon_\lambda(T)\phi^b_\lambda(T)$ **…very useful!**

Illustrative example:



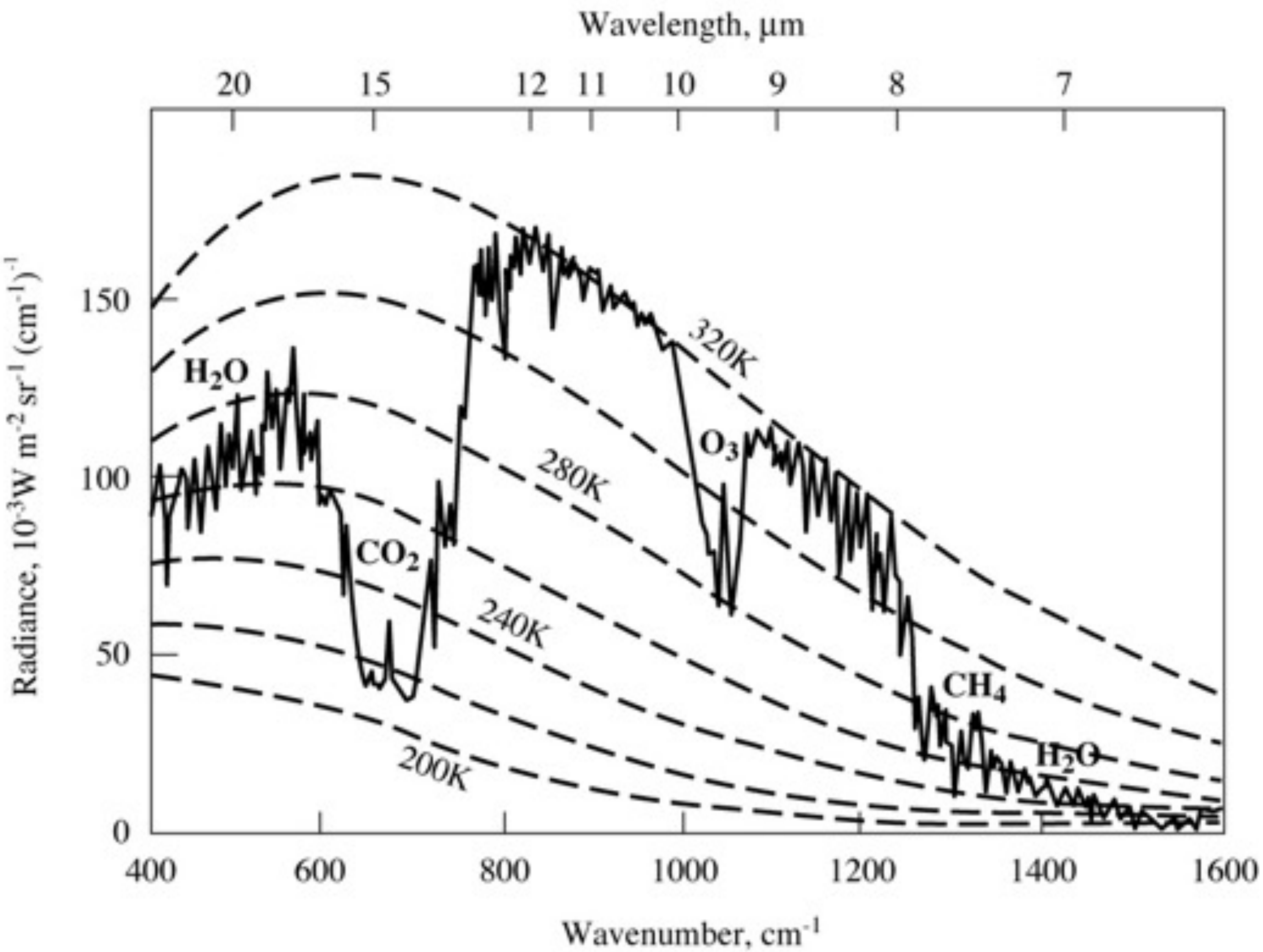
Kirchhoff's law allows determination of the emission spectrum of any object solely from knowledge of its absorption spectrum and its temperature

SOLAR RADIATION SPECTRUM: blackbody at 5800 K

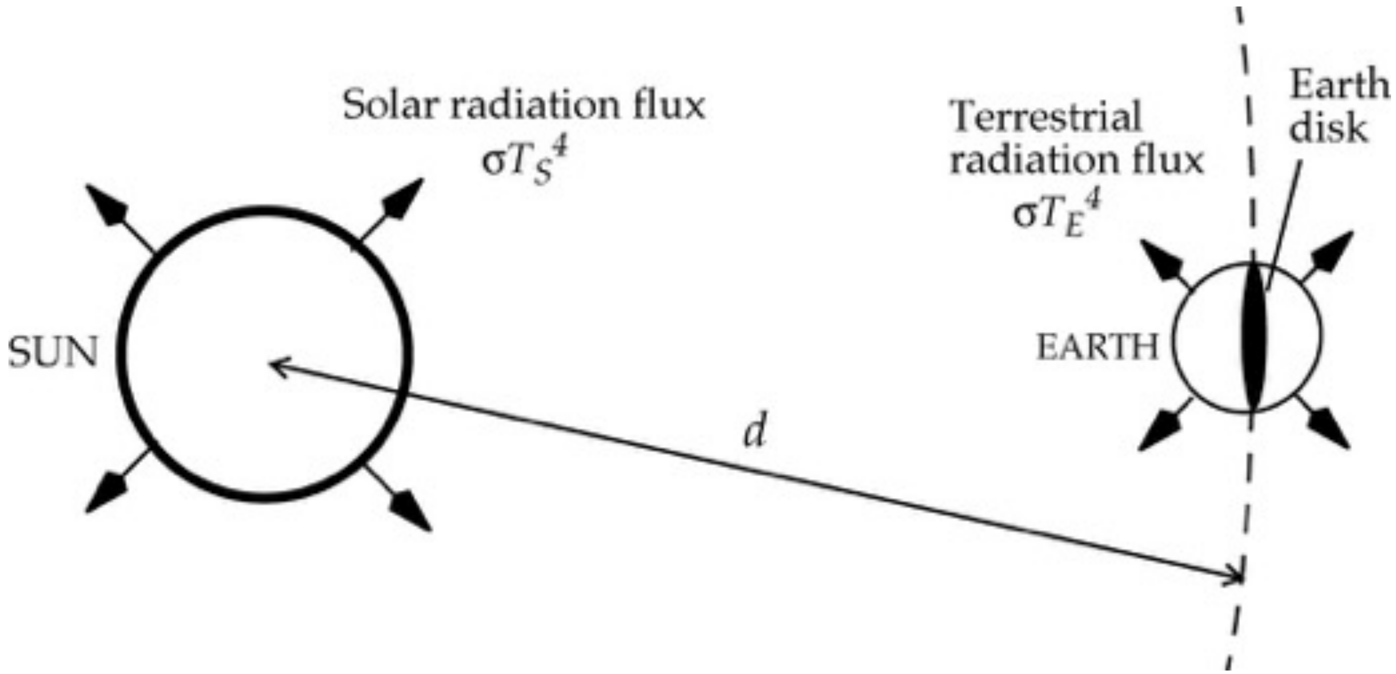


TERRESTRIAL RADIATION SPECTRUM FROM SPACE: composite of blackbody radiation spectra for different *T*

Scene over Niger valley, N Africa



RADIATIVE EQUILIBRIUM FOR THE EARTH



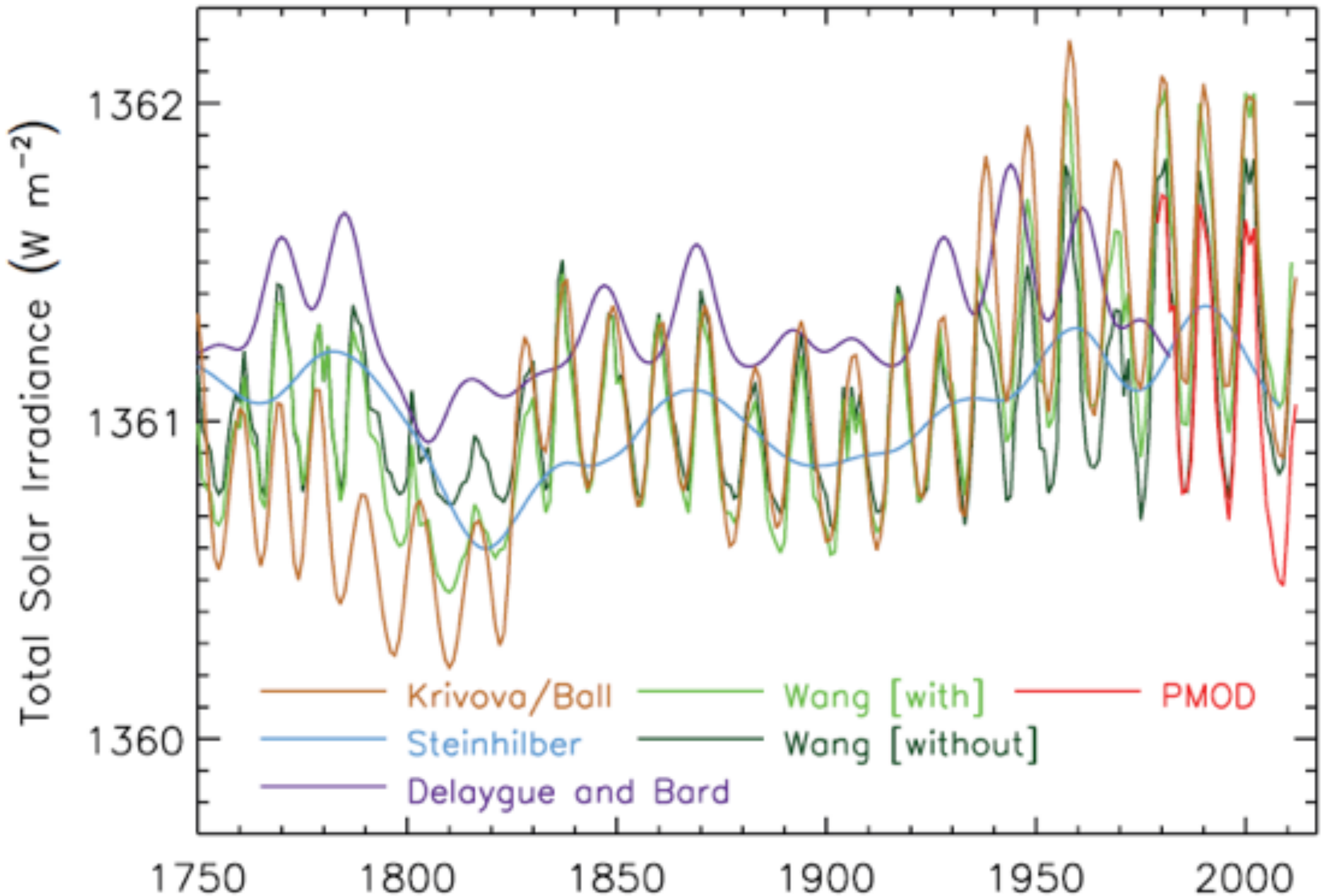
Solar radiation flux intercepted by Earth = solar constant $F_S = 1361$ W m^{-2}

Radiative balance ⇨ effective temperature of the Earth:

$$T_E = \left[\frac{F_S(1-A)}{4\sigma}\right]^{\frac{1}{4}} = 255 \text{ K}$$

where *A* is the albedo (reflectivity) of the Earth

Total solar irradiance a.k.a. “solar constant” vs. time



IPCC [2014]

ABSORPTION OF RADIATION BY GAS MOLECULES

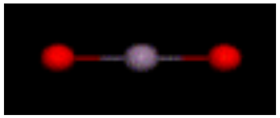
…requires quantum transition in internal energy of molecule.

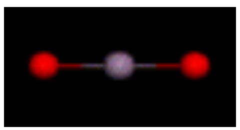
- THREE TYPES OF TRANSITION
  - Electronic transition: UV radiation (<0.4 μm)
    - Jump of electron from valence shell to higher-energy shell, may result in photolysis (example: $O_3 + h\nu \rightarrow O_2 + O$)
  - Vibrational transition: near-IR (0.7-20 μm)
    - Increase in vibrational frequency of a given bond

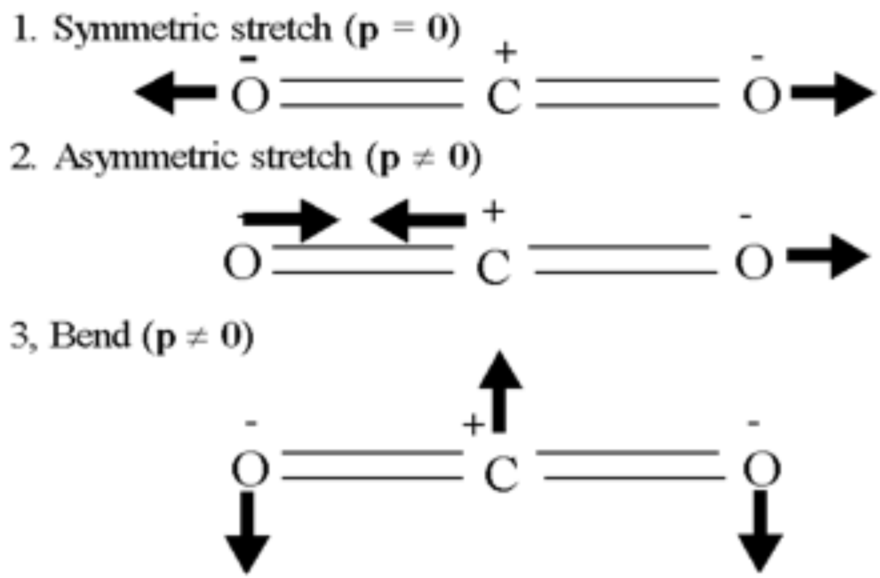
    requires change in dipole moment of molecule
  - Rotational transition: far-IR (20-100 μm)
    - Increase in angular momentum around rotation axis

Gases that absorb radiation near the spectral maximum of terrestrial emission (10 μm) are called *greenhouse gases;* this requires vibrational or vibrational-rotational transitions

NORMAL VIBRATIONAL MODES OF CO_2





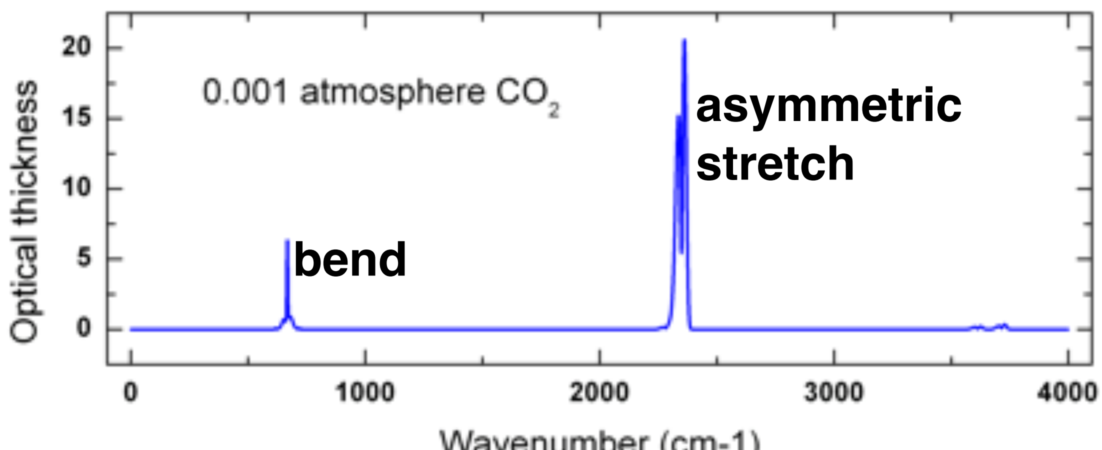


$\Delta p = 0$ **forbidden**

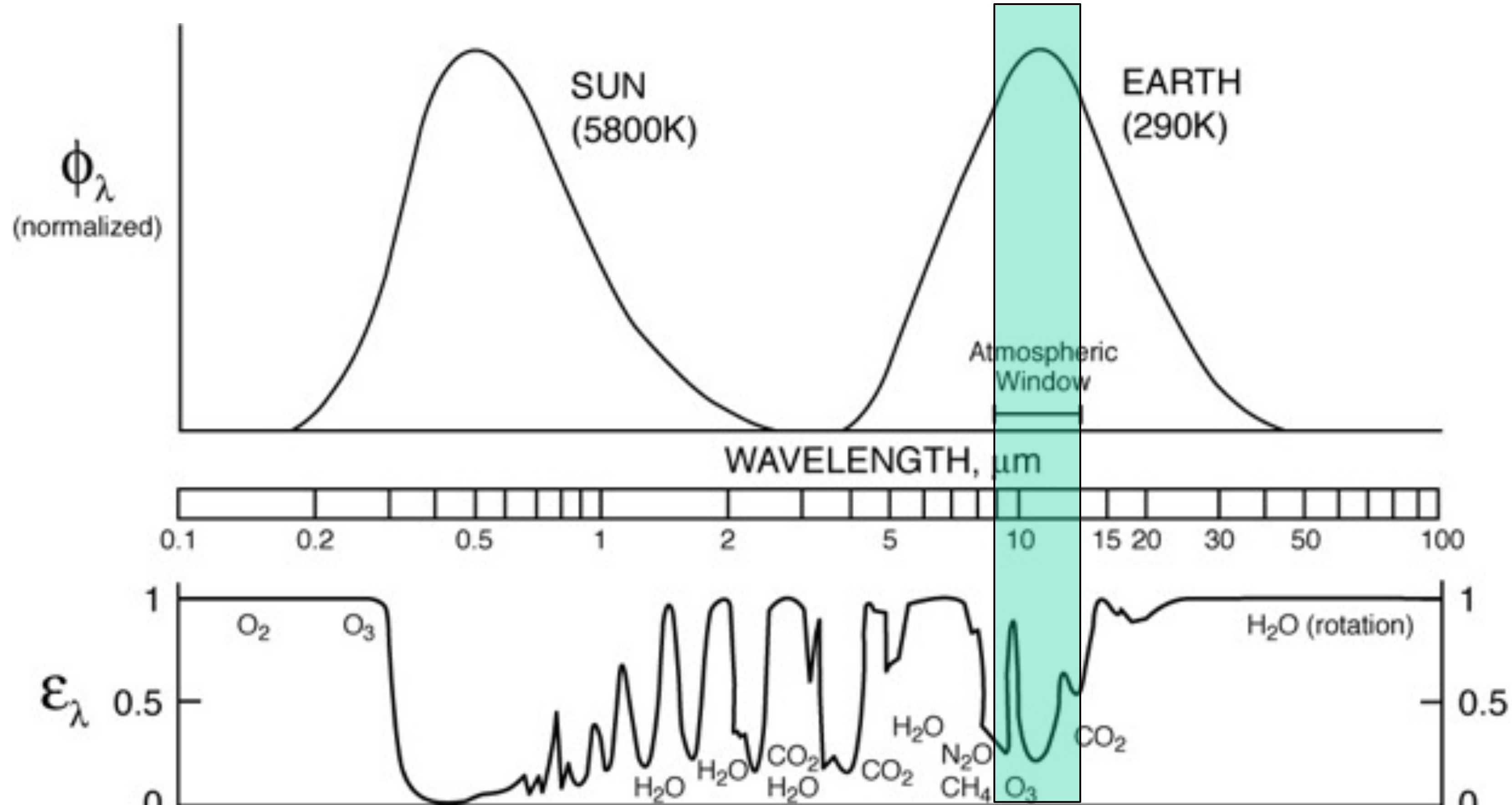
$\Delta p \neq 0$ **allowed**

$\Delta p \neq 0$ **allowed**

IR spectrum of CO_2



GREENHOUSE EFFECT: absorption of terrestrial radiation by the atmosphere



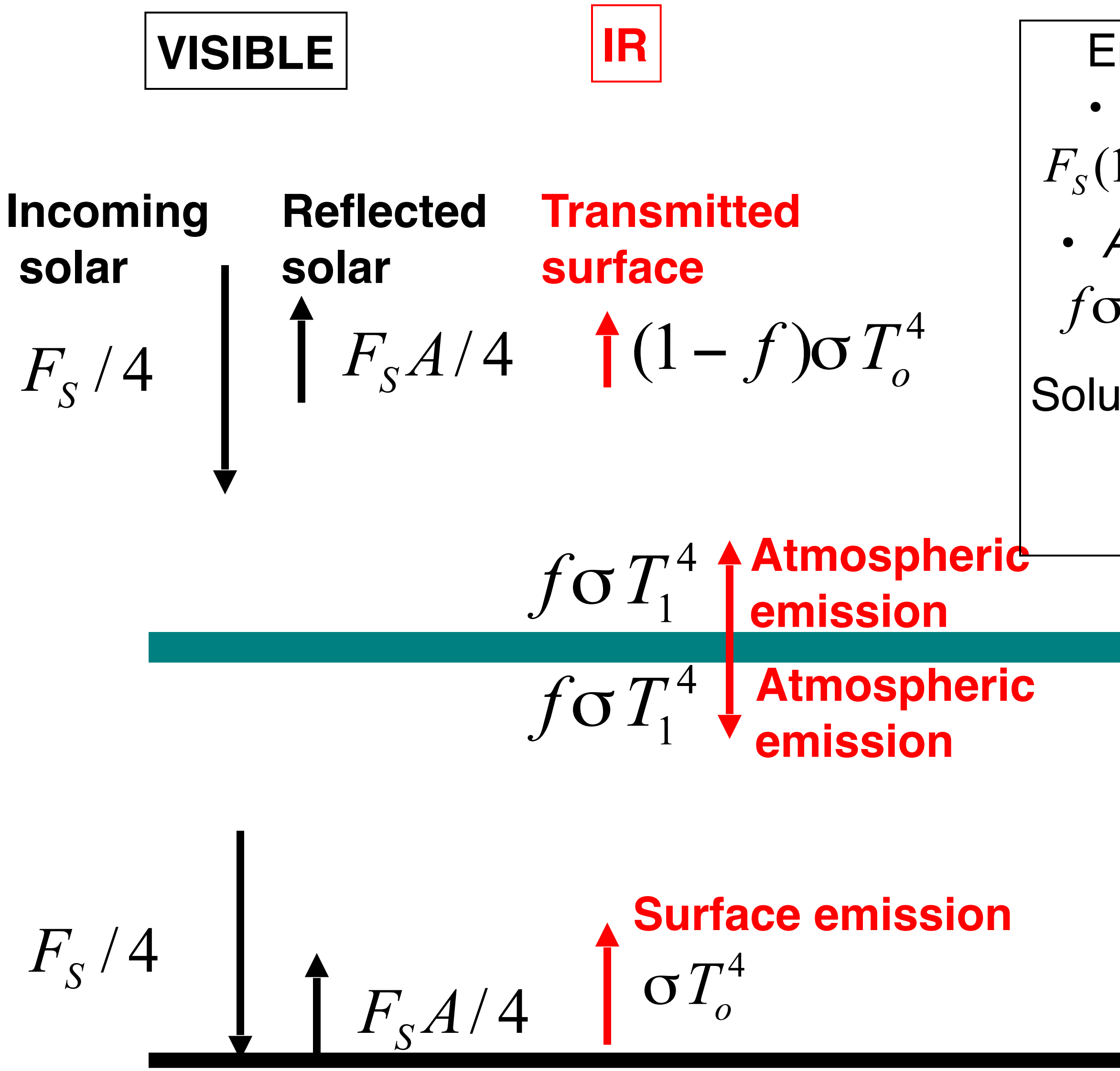
- Major greenhouse gases: H_2O, CO_2, CH_4, O_3, N_2O, CFCs,…
- Not greenhouse gases: N_2, O_2, Ar, …

Questions

1. The Earth emits as a blackbody. However, it absorbs only 72% of solar radiation (albedo = 0.28), so obviously is not a very good blackbody (which would absorb 100% of all incoming radiation). How do you resolve this apparent contradiction?

2. Which of these molecules are greenhouse gases: SO_2, CO, H_2 ?

SIMPLE MODEL OF GREENHOUSE EFFECT



Energy balance equations:

- *Earth system*

$$F_S(1 - A)/4 = (1 - f)\sigma T_o^4 + f \sigma T_1^4$$

- *Atmospheric layer*

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

Solution:

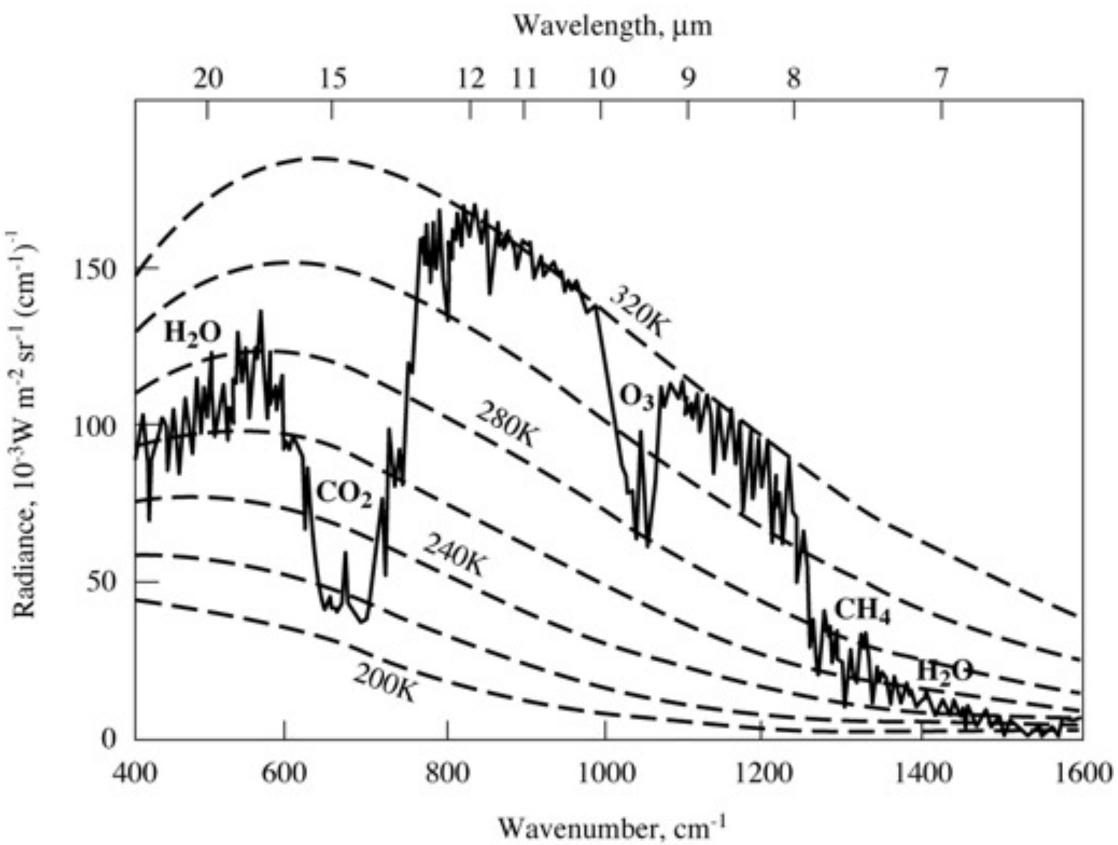
$$T_o = \left[\frac{F_S(1 - A)}{4(1 - \frac{f}{2})\sigma} \right]^{\frac{1}{4}}$$

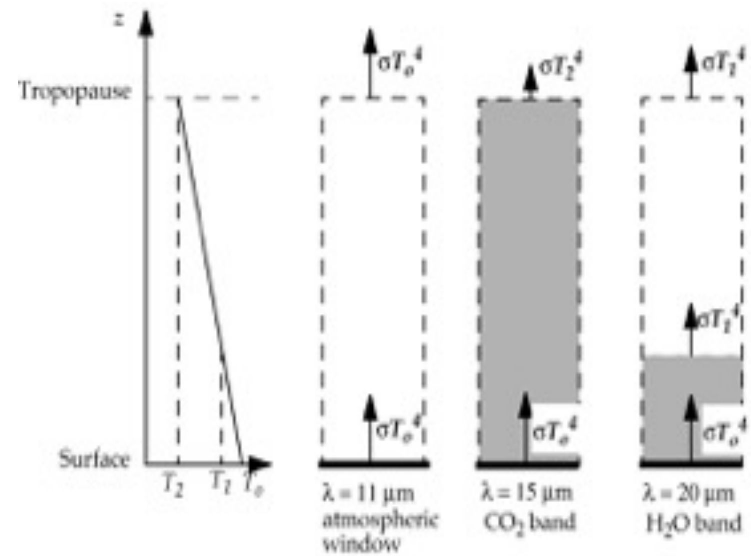
TT_o **= 288 K** ⇨ ***f* = 0.77**, T_1 **= 241 K**

Atmospheric layer (T_1)
abs. eff. 0 for solar (VIS)
***f* for terr. (near-IR)**

Earth surface (T_o)
Absorption efficiency 1-*A* in VISIBLE
1 in IR

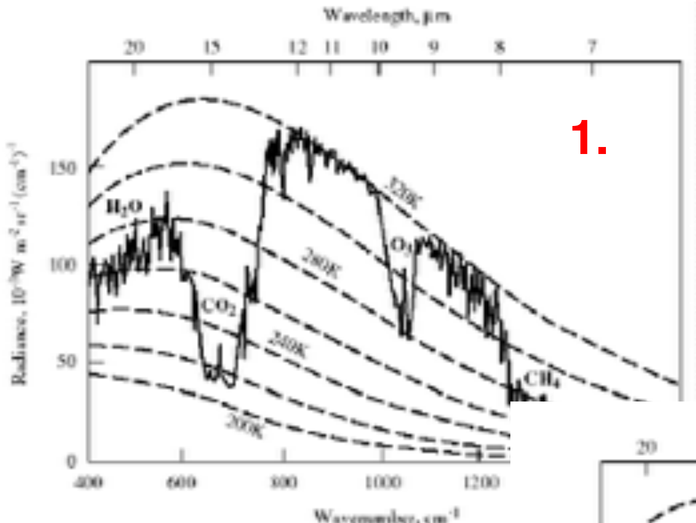
TERRESTRIAL RADIATION SPECTRUM FROM SPACE: composite of blackbody radiation spectra for different *T*



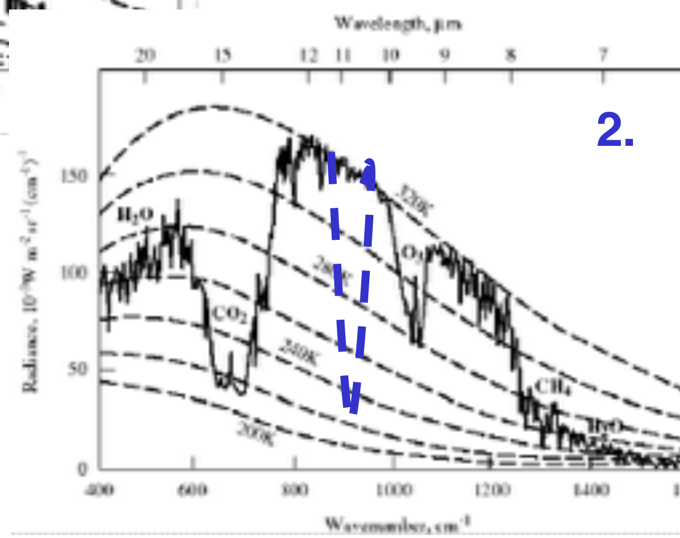


HOW DOES ADDITION OF A GREENHOUSE GAS WARM THE EARTH?

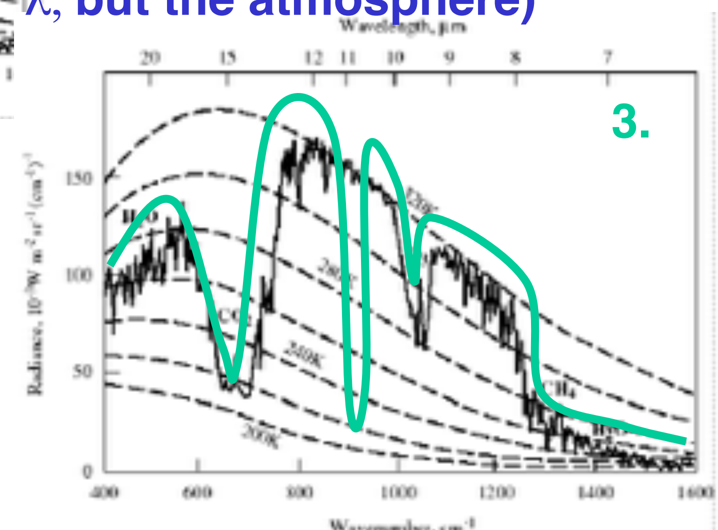
Example of a GG absorbing at 11 μm



1. Initial state



2. Add to atmosphere a GG absorbing at 11 μm; emission at 11 μm decreases (we don't see the surface anymore at that λ, but the atmosphere)

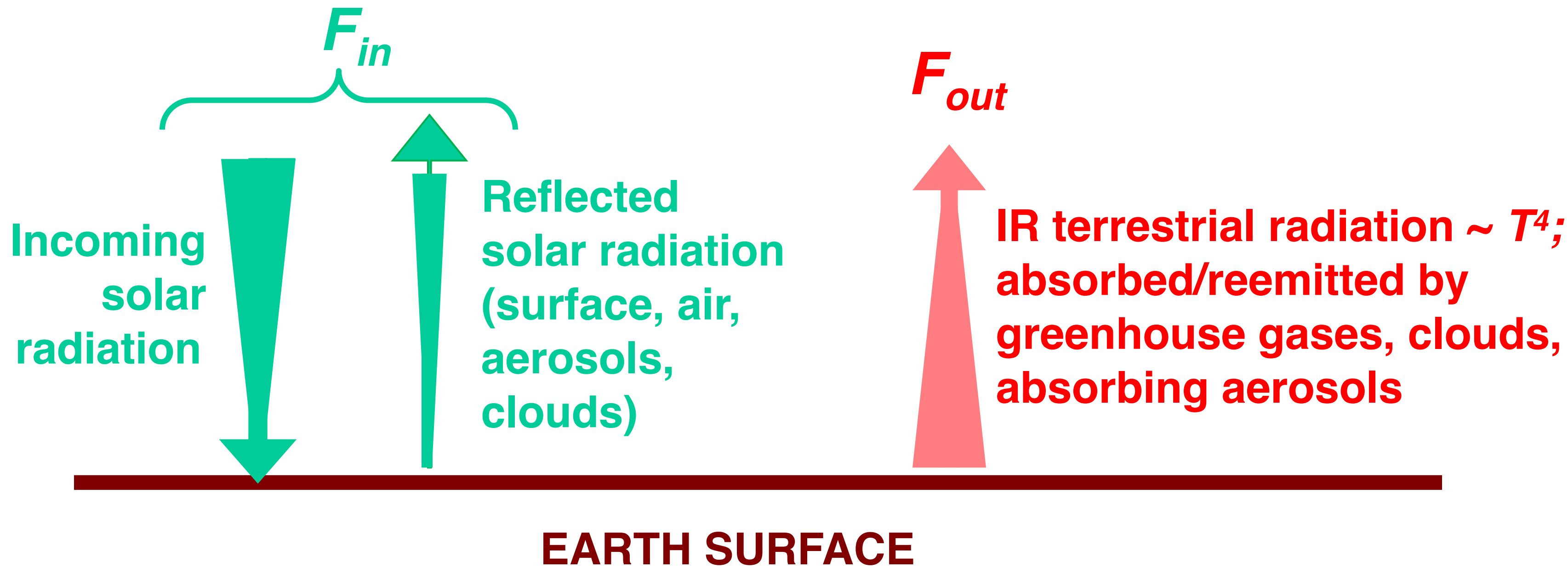


3. At new steady state, total emission integrated over all λ's must be conserved

⇨ Emission at other λ's must increase

⇨ The Earth must heat!

RADIATIVE FORCING OF CLIMATE CHANGE



- Stable climate is defined by radiative equilibrium: $F_{\text{in}} = F_{out}$
- Instantaneous perturbation ⇨ Radiative forcing $\Delta F = F_{in} - F_{out}$

  Increasing greenhouse gases → $\Delta F > 0$ positive forcing

- The radiative forcing changes the heat content H of the Earth system:

$$\frac{dH}{dt} = \Delta F - \frac{\Delta T_o}{\lambda}$$ eventually leading to new steady state $$\Delta T_o = \lambda \Delta F$$

where T_o is the surface temperature and λ is a climate sensitivity parameter

- IPCC climate models give λ = 0.3-1.4 K m^2 W^{-1}, insensitive to nature of forcing; differences between models reflect different treatments of feedbacks

Deriving the climate sensitivity parameter from our simple greenhouse model

At starting climate equilibrium,

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

Increase atmospheric layer absorptivity by *df*: resulting radiative forcing *dF* is

$$dF = dF_{in} - dF_{out} = -dF_{out} = -\left(\left[1-\frac{f+df}{2}\right]\sigma T_o^4 - \left[1-\frac{f}{2}\right]\sigma T_o^4\right) = \frac{df}{2}\sigma T_o^4$$

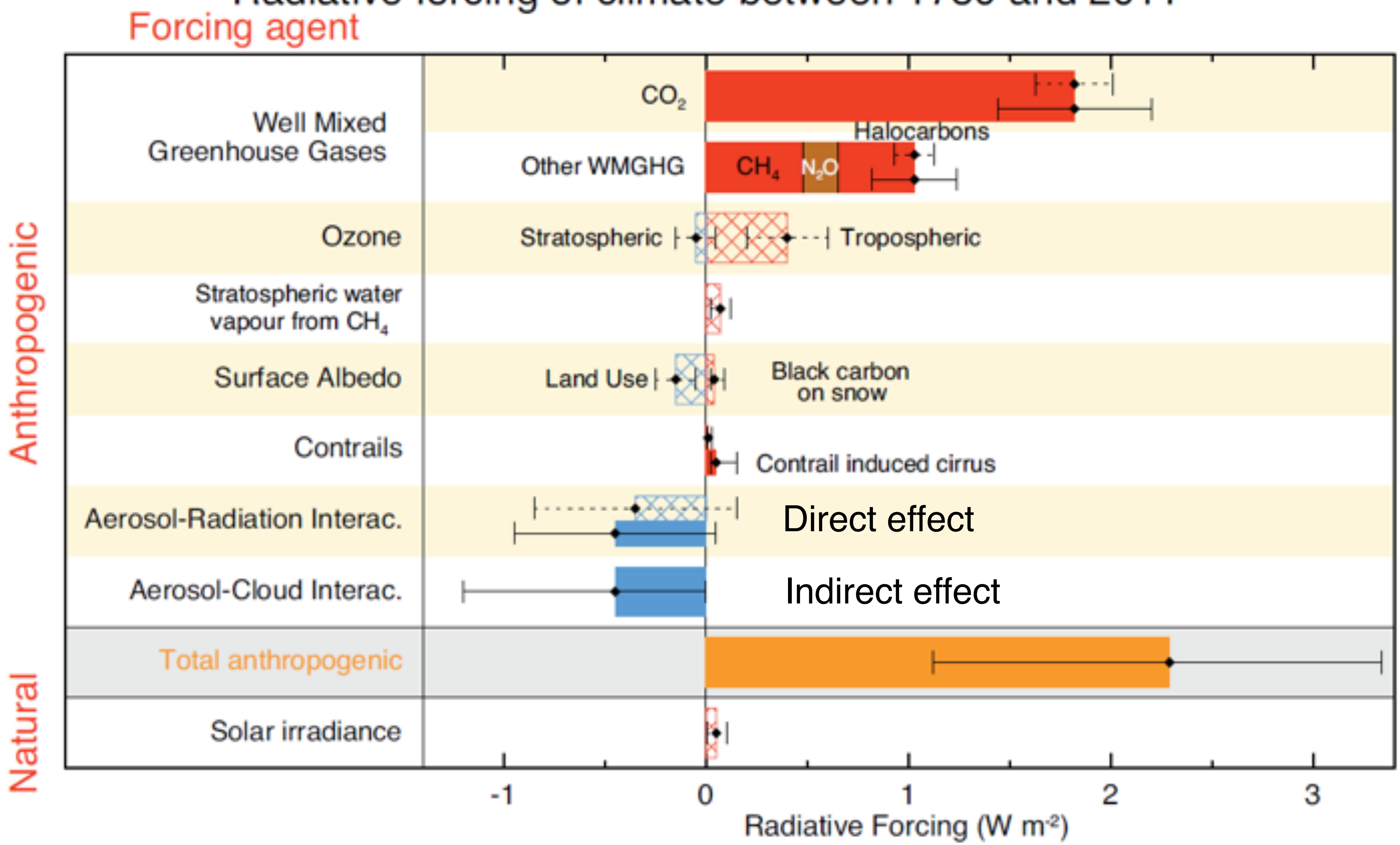
Eventually, the climate adjusts to new equilibrium:

$$\frac{F_S(1-A)}{4} = \left[1-\frac{f+df}{2}\right]\sigma\left[T_o + dT_o\right]^4 \approx \left[1-\frac{f+df}{2}\right]\sigma[T_o^4 + 4T_o^3 dT_o]$$

which implies

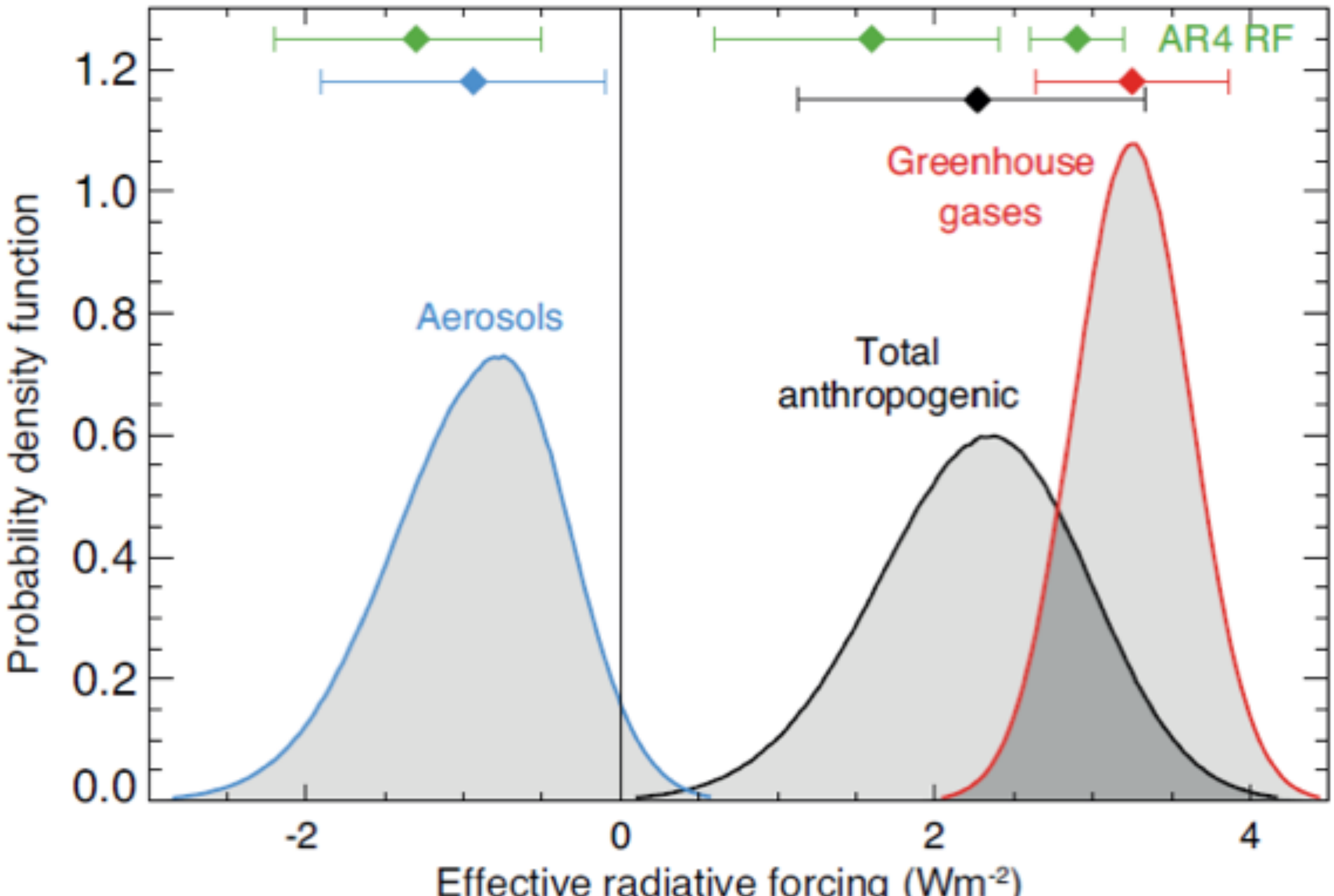
$$dT_o = \lambda dF \quad \text{with} \quad \lambda = \left[[1-\frac{f}{2}]4\sigma T_o^3\right]^{-1} = 0.3 \text{ K m}^2 \text{ W}^{-1}$$

Radiative forcing of climate between 1750 and 2011



IPCC [2014]

Effect of aerosols on radiative forcing and its uncertainty



IPCC [2014]

Scattering and absorption of solar radiation by aerosols: "aerosol-radiation interactions"

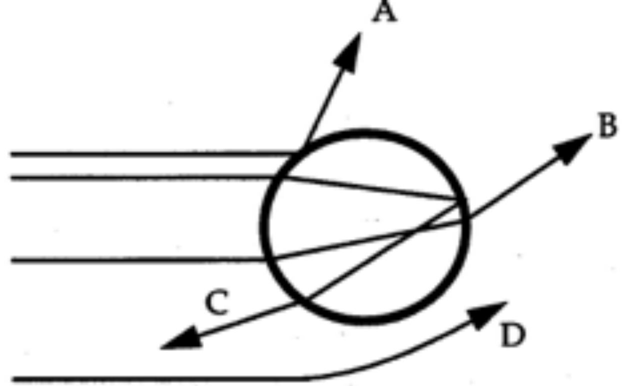
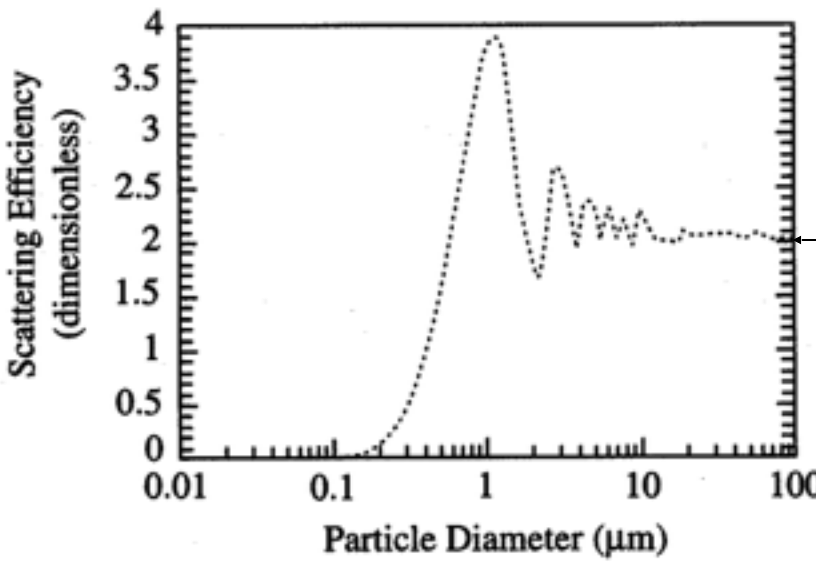


Fig. 8-3 Scattering of a radiation beam: processes of reflection (A), refraction (B), refraction and internal reflection (C), and diffraction (D).

By scattering solar radiation, aerosols increase the Earth's albedo

Scattering efficiency is maximum when particle radius = λ
⇨particles in 0.1-1 μm size range are efficient scatterers of solar radiation



2 (diffraction limit)

Fig. 8-4 Scattering efficiency of green light (λ = 0.5 μm) by a liquid water sphere as a function of the diameter of the sphere. Scattering efficiencies can be larger than unity because of diffraction. Adapted from Jacobson, M. Z. *Fundamentals of Atmospheric Modeling*. Cambridge, England: Cambridge University Press, 1999.

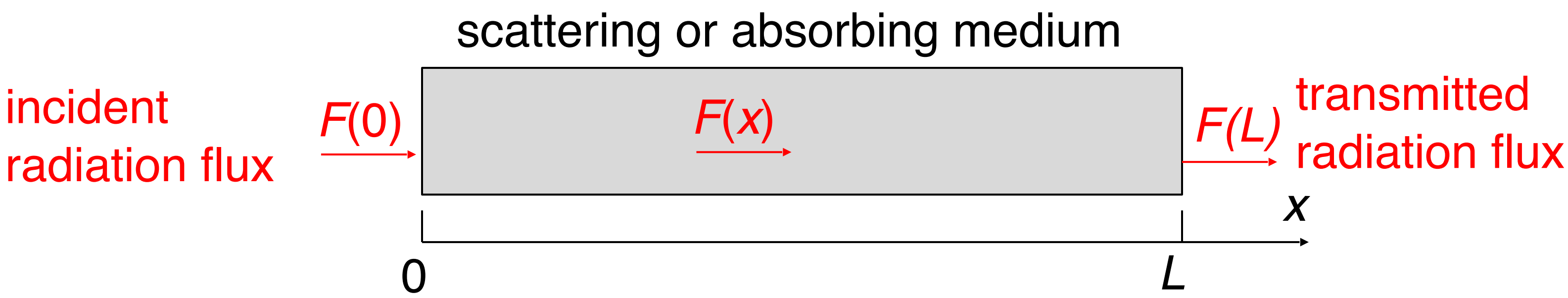
Scattering and absorbing aerosols

Scattering sulfate and organic aerosol over Massachusetts

Partly absorbing dust aerosol downwind of Sahara

Absorbing aerosols (soot, dust) can warm the climate by absorbing solar radiation

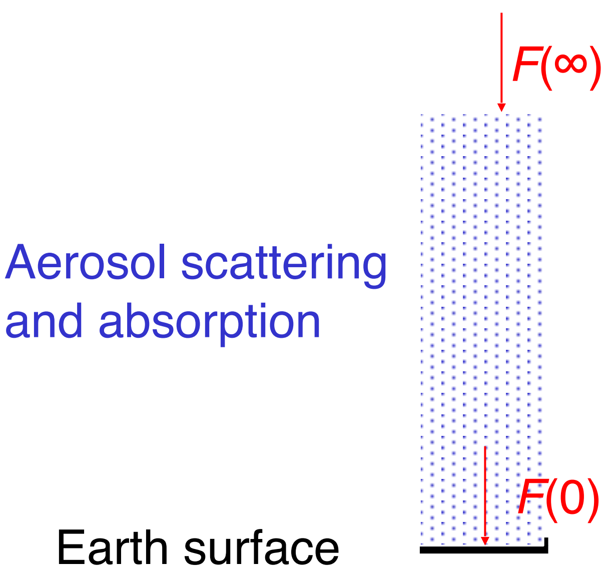
Optical depth



Beer's law: $dF = -kFdx$ where *k* [m-1] is a scattering+absorption coefficient

Integrate: $F(L) = F(0)\exp[-\delta]$ where $\delta = \int_0^L k(x)dx$ is the optical depth

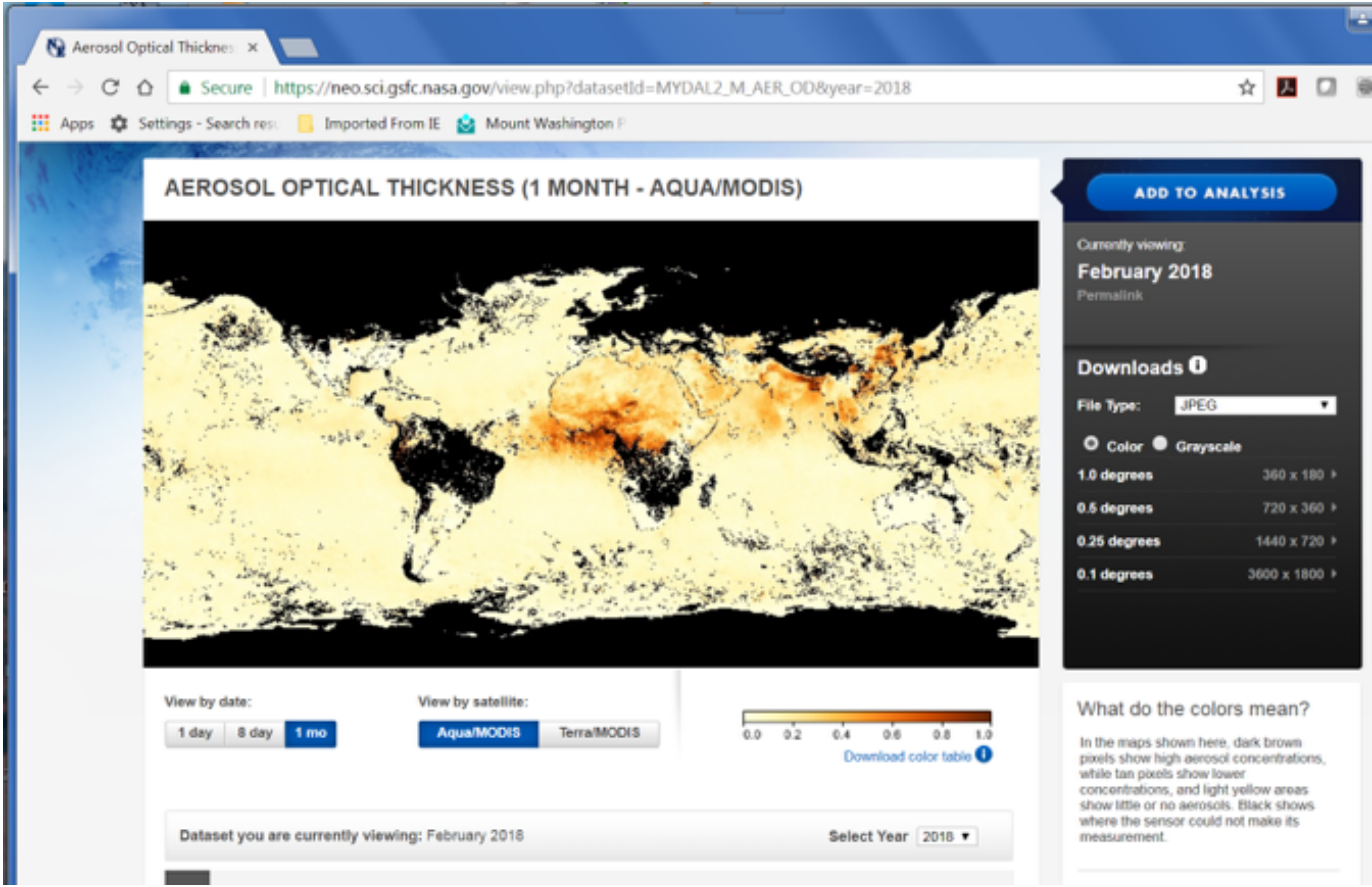
Application to atmospheric aerosol:



Aerosol optical depth (AOD)
a.k.a. aerosol optical thickness (AOT):

$$AOD = \ln[F(\infty)/F(0)]$$

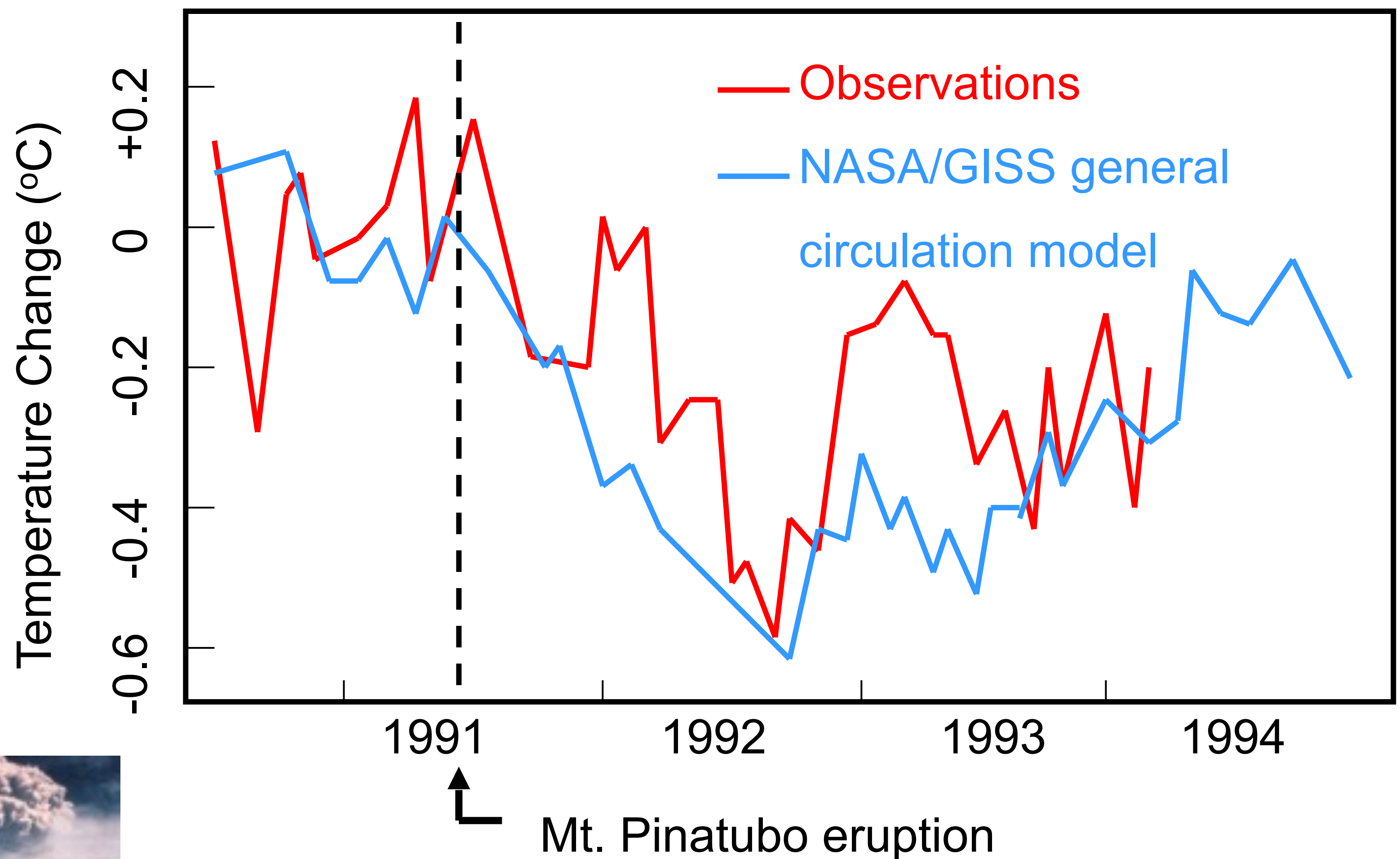
Aerosol optical depth (or thickness, same thing)



[Model movie of aerosol optical depth]

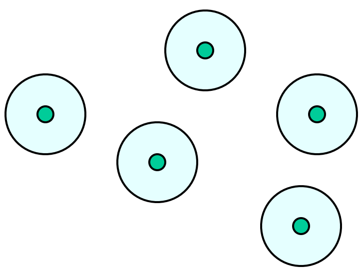
EVIDENCE OF AEROSOL EFFECTS ON CLIMATE:

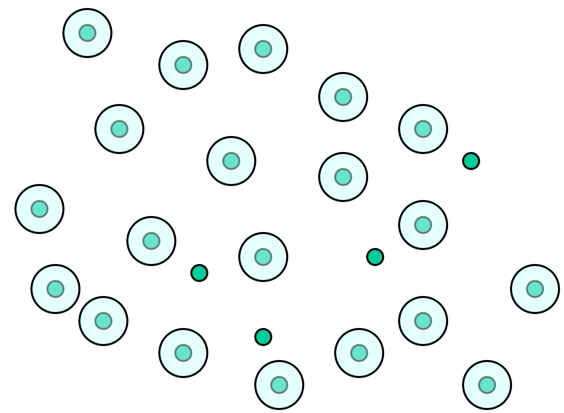
Temperature decrease following large volcanic eruptions



Radiative forcing from aerosol-cloud interactions

Clouds form by condensation on preexisting aerosol particles (“cloud condensation nuclei”)when RH>100%





clean cloud (few particles): large cloud droplets
- low albedo
- efficient precipitation

polluted cloud (many particles): small cloud droplets
- high albedo
- suppressed precipitation

Questions

1. Fuel combustion emits water vapor. This water vapor has negligible greenhouse warming effect when emitted from cars in surface air, but it has a strong greenhouse warming effect when emitted from aircraft at the tropopause. Explain why.

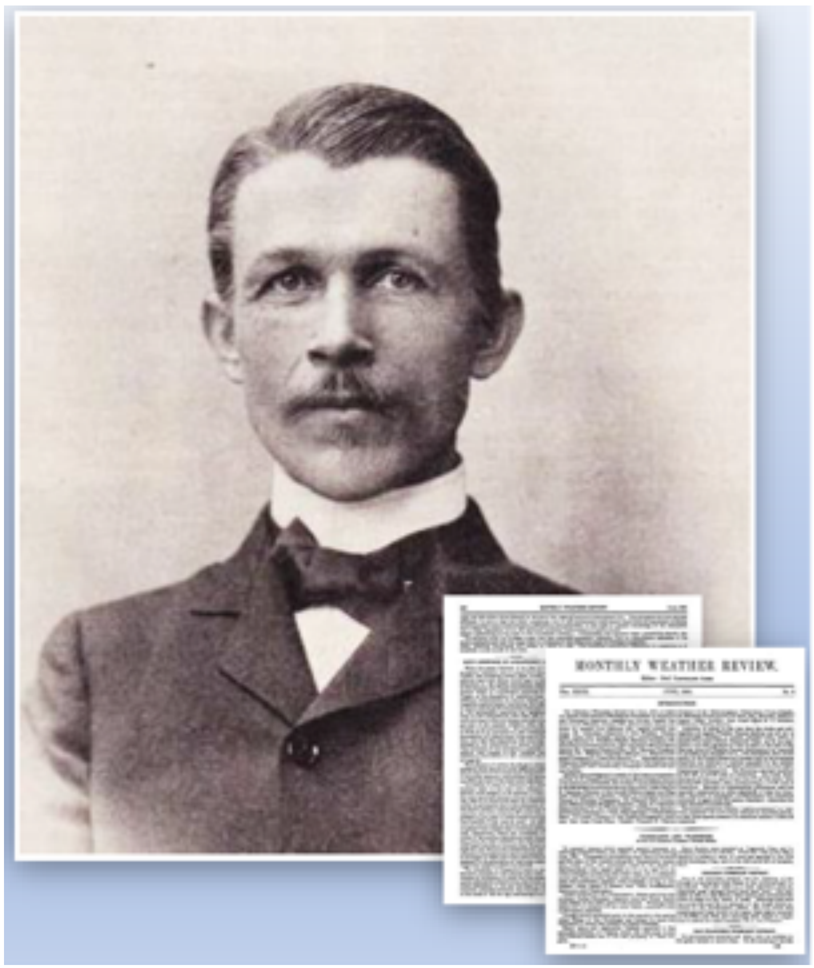
2. A climate skeptic argues, “It’s ridiculous to think that CO_2 could be causing climate warming, considering [which is true] that water vapor is so much more important than CO_2 as a greenhouse gas!” How do you respond?

First prediction of anthropogenic CO_2 greenhouse effect (1896)

Svante Arrhenius
(1859-1927)

- Volcanic e[illegible] of CO[illegible] cause of the ice ages
- Coal emissions of CO_2 are causing warming of the atmosphere
- A doubling of CO_2 would cause a 4^{o}C temperature increase

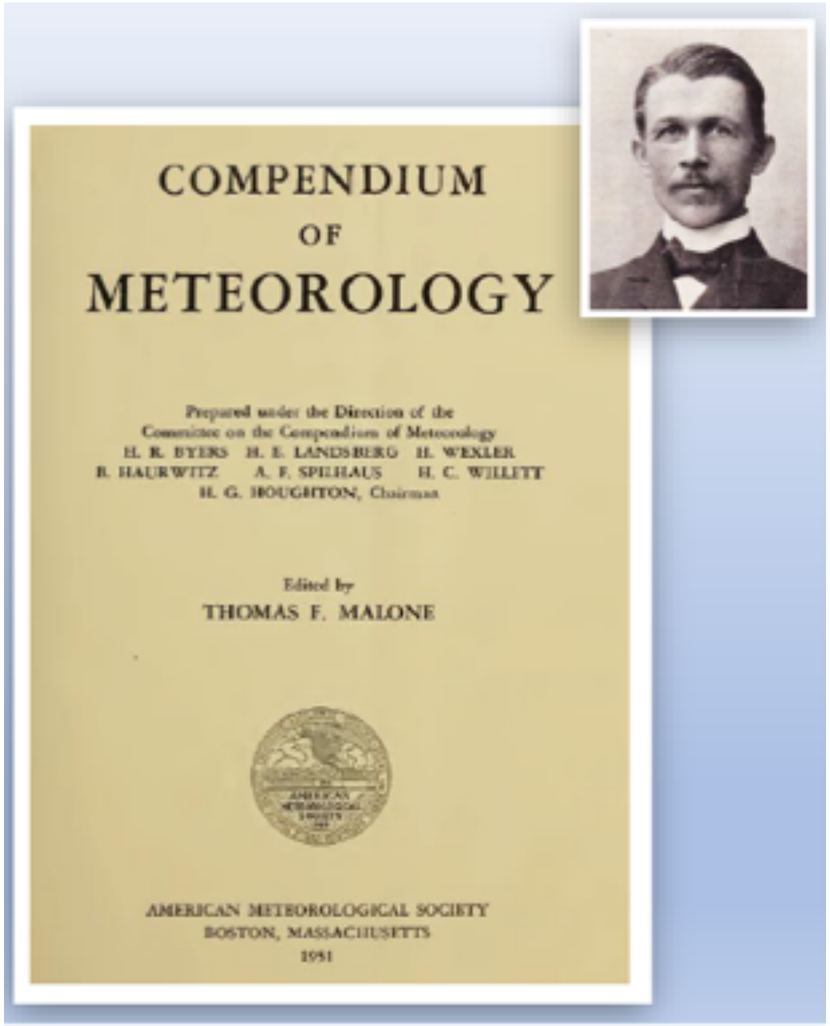
The first climate skeptic: Knut Angstrom (1900)



"The remainder of Angstrom's paper is devoted to a destructive criticism of the theories put forth by the Swedish chemist, S. Arrhenius, in which the total absorption of CO_2 is quite inadmissibly inferred from data which include the combined absorption of CO_2 and the vapor of water."

US Dept. of Agriculture, Monthly Weather Review (June 1, 1901) p.268

Angstrom's view prevailed until the 1950s



"[Arrhenius] saw in this a cause of climactic changes, but the theory was never widely accepted and was abandoned when it was found that all the long-wave radiation absorbed by CO_2 is also absorbed by water vapor."

American Meteorological Society Compendium of Meteorology , 1951

What made it change?

- Realization that CO_2 absorbed at different wavelengths than H_2O
- Realization that CO_2 extended to higher altitudes than H_2O