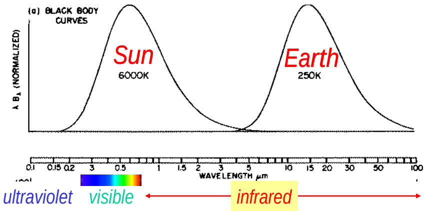
Energy Inputs and Outputs

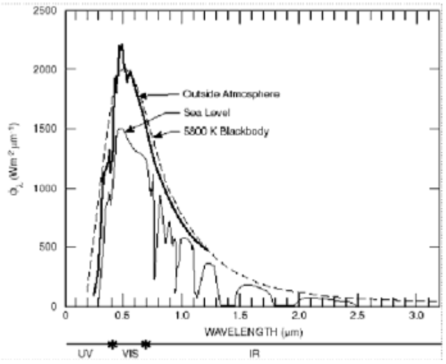


- Both Sun and Earth behave as blackbodies (absorb 100% incident radiation; emit radiation at all wavelengths in all directions)

- Earth receives energy from sun in the form of shortwave radiation with peak in the visible ($\lambda = 0.4 - 0.7\ \mu m$)

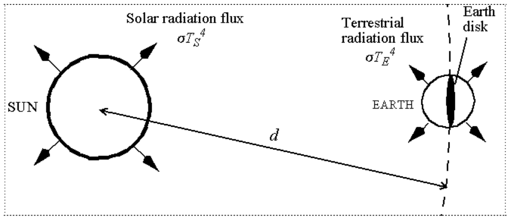
- Earth emits energy to space in the form of longwave radiation in the infrared ($\lambda = 5\text{-}20\ \mu m$) → function of Earth's temperature

SOLAR RADIATION SPECTRUM:
blackbody at 5800 K



Total Solar Radiation Received By Earth

- Solar constant for Earth: 1368 W m^{-2} (Note: 1 W = 1 J s^{-1})



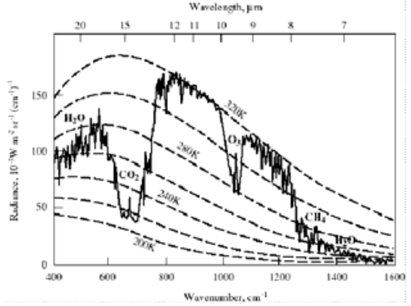
- Solar radiation received top of atmosphere unit area of sphere = (1368) x $(\pi r_e^2)/(4 \pi r_e^2)$ = 342 W m^{-2}

A No-Atmosphere Earth

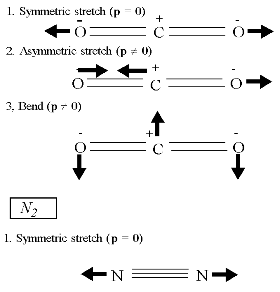
- Assume 30% of incoming solar energy is reflected by surface (albedo of surface = 0.3)
- Energy absorbed by surface = 70% of 342 W m^{-2} = 239.4 W m^{-2}
- Balanced by energy emitted by surface
- Stefan-Boltzmann law: Energy emitted = σT^4 ;(σ=5.67 x 10^{-8} W m^{-2} K^{-4})
- 239.4 W m^{-2} = σT^4 → T = 255 K (-18°C)
  - → much less than average temperature of 288 K (15°C)
- What is missing?
  - → Absorption of terrestrial radiation by the atmosphere

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

Scene over Niger valley, N Africa (noon)



NORMAL VIBRATIONAL MODES OF CO_2

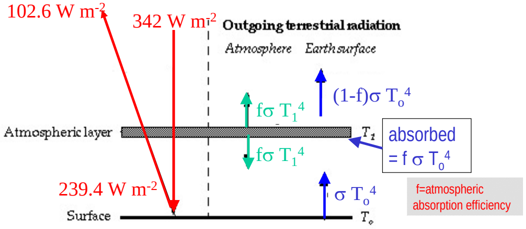


Greenhouse gases = gases with vib-rot absorption features at 5-50 µm

- **Major greenhouse gases: H_2O, CO_2, CH_4, O_3, N_2O, CFCs,…**
- **<u>Not</u> greenhouse gases: N_2, O_2, Ar, …**

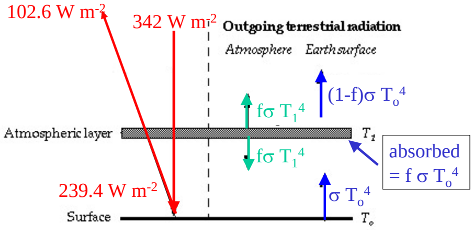
Molecules that can acquire a charge assymetry be stretching or flexing are greenhouse gases.

An Idealized Earth+Atmosphere



- Solar radiation at surface = 70% of 342 W m^{-2} = 239.4 W m^{-2}
- Infrared flux from surface = σT_o^4
- Absorption of infrared flux by atmosphere = $f \sigma T_o^4$
- Kirchhoff's law: efficiency of absorption = efficiency of emission
- IR flux from atmospheric layer = $f \sigma T_1^4$ (up and down)
- IR flux to space = $f \sigma T_1^4 + (1-f)\sigma T_o^4$

Radiation Balance Equations



- Balance at top of atmosphere

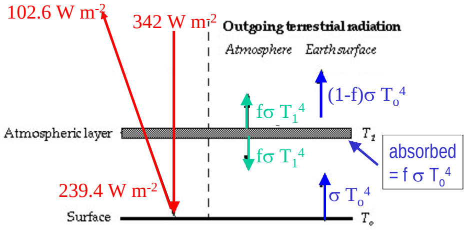
$$f \sigma T_1^4 + (1-f) \sigma T_o^4 = 239.4$$

- Balance for atmospheric layer

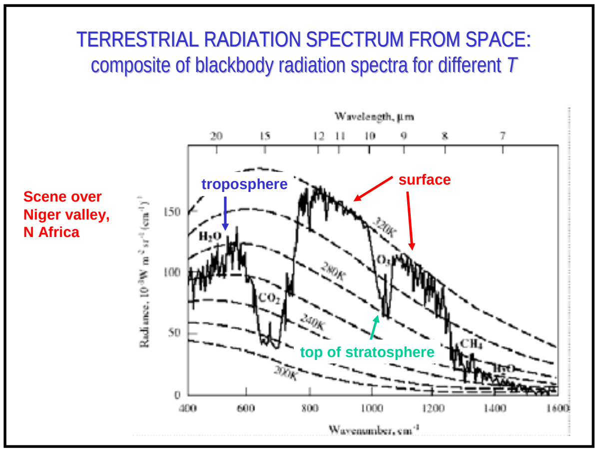
$$f \sigma T_1^4 + f \sigma T_1^4 = f \sigma T_o^4$$

→ Solve for T_o and T_1

The Greenhouse Effect

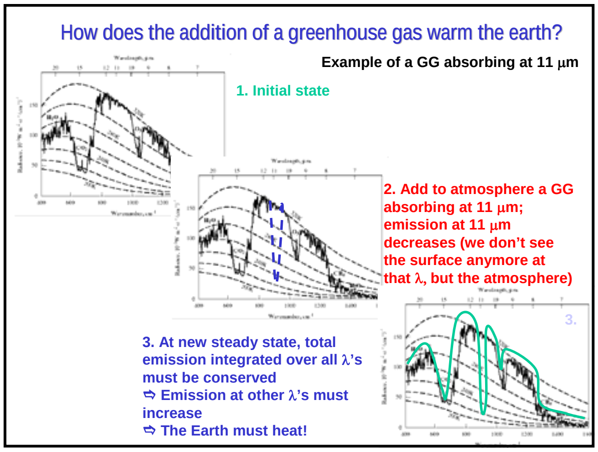


- For f=0.77, T_o=288 K and T_1=242 K (33 K warmer than the no-atmosphere case)
- As f increases, T_o and T_1 increase
- Greenhouse gases → gases that affect f (absorption efficiency of atmos.)
- Earth has a natural greenhouse effect; human activities enhance effect



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

Scene over
Niger valley,
N Africa



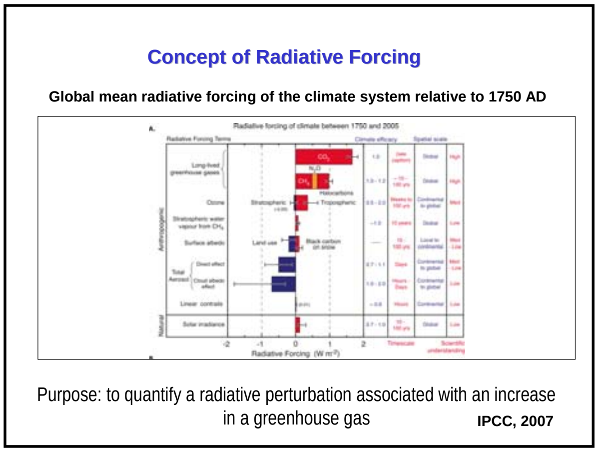
How does the addition of a greenhouse gas warm the earth?

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!



Concept of Radiative Forcing

Global mean radiative forcing of the climate system relative to 1750 AD

Purpose: to quantify a radiative perturbation associated with an increase in a greenhouse gas

IPCC, 2007

Aerosol direct and indirect effects

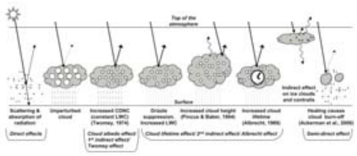


Figure 2.10

IPCC, 2007

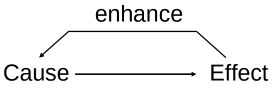
Radiative Forcing and Temperature Change

- •Increasing the abundance of a greenhouse gas by Δm corresponds to an increase in Δf of the absorption efficiency, and an initial decrease in IR radiation emitted to space (by ΔF)
- •Response of system to energy imbalance: → T_0 and T_1 increase
→ may cause other greenhouse gases to change
→ T_0 and T_1 may increase or decrease depending on internal climate *feedbacks*
→ Δf → ΔT → etc… → Ultimately, the system gets back in balance

- Radiative forcing is only a measure of initial change in outgoing terrestrial radiation

- Climate models (GCMs) indicate $\Delta T_{surface} = \lambda \, \Delta F$ where λ (climate sensitivity parameter) ranges from 0.3 to 1.4 K m^2 W^{-1} depending on the GCM

Positive Feedback


enhance

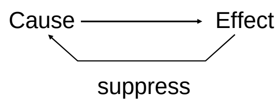
Cause → Effect

Effect enhances cause
→ increase effect
→ boom!!!

Ex: Water vapor feedback
Ex: warmer → melting land ice → lower albedo → further warming

Negative Feedback

Negative feedback



Cause → Effect

suppress

Effect suppresses cause
→ decrease effect
→ "self-regulation"

Example: warmer → more clouds → higher albedo → cooling effect (negative feedback)

Feedbacks

- **water vapor feedback:** positive.

CO_2 → Temperature ⇄ Water vapor

Greenhouse effect

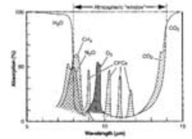
Greenhouse effect

- **ice-albedo feedback:** positive or negative?.
- **cloud feedbacks:** positive or negative? potentially large *(clouds can reflect solar radiation or absorb IR radiation depending on their height, thickness and microphysical properties)* Largest uncertainty in current estimates of climate change.
- **land surface feedback:** positive or negative? (surface albedo affect, CO_2 fertilization, soil moisture)

GLOBAL WARMING POTENTIAL (GWP):
foundation for climate policy

- The GWP measures the integrated radiative forcing over a time horizon Δt from the injection of 1 kg of a species X at time t_o, relative to CO_2:

$$\mathrm{GWP} = \frac{\int_{t_o}^{t_o+\Delta t} \Delta F_{1\,\mathrm{kg\,X}}\,dt}{\int_{t_o}^{t_o+\Delta t} \Delta F_{1\,\mathrm{kg\,CO_2}}\,dt}$$



Gas	Lifetime (years)	GWP for time horizon		
		20 years	100 years	500 years
CO_2	~100	1	1	1
CH_4	12	63	23	7
N_2O	114	279	300	158
CFC-12 (CF_2Cl_2)	100	10340	10720	5230
HFC-134a (CH_2FCF_3)	14	3580	1400	400
SF_6	3200	15290	22450	32780