Greenhouse Effects & Radiative Forces

Reference: Introduction to Atmospheric Chemistry by Daniel J. Jacob, Princeton University Press, 1999

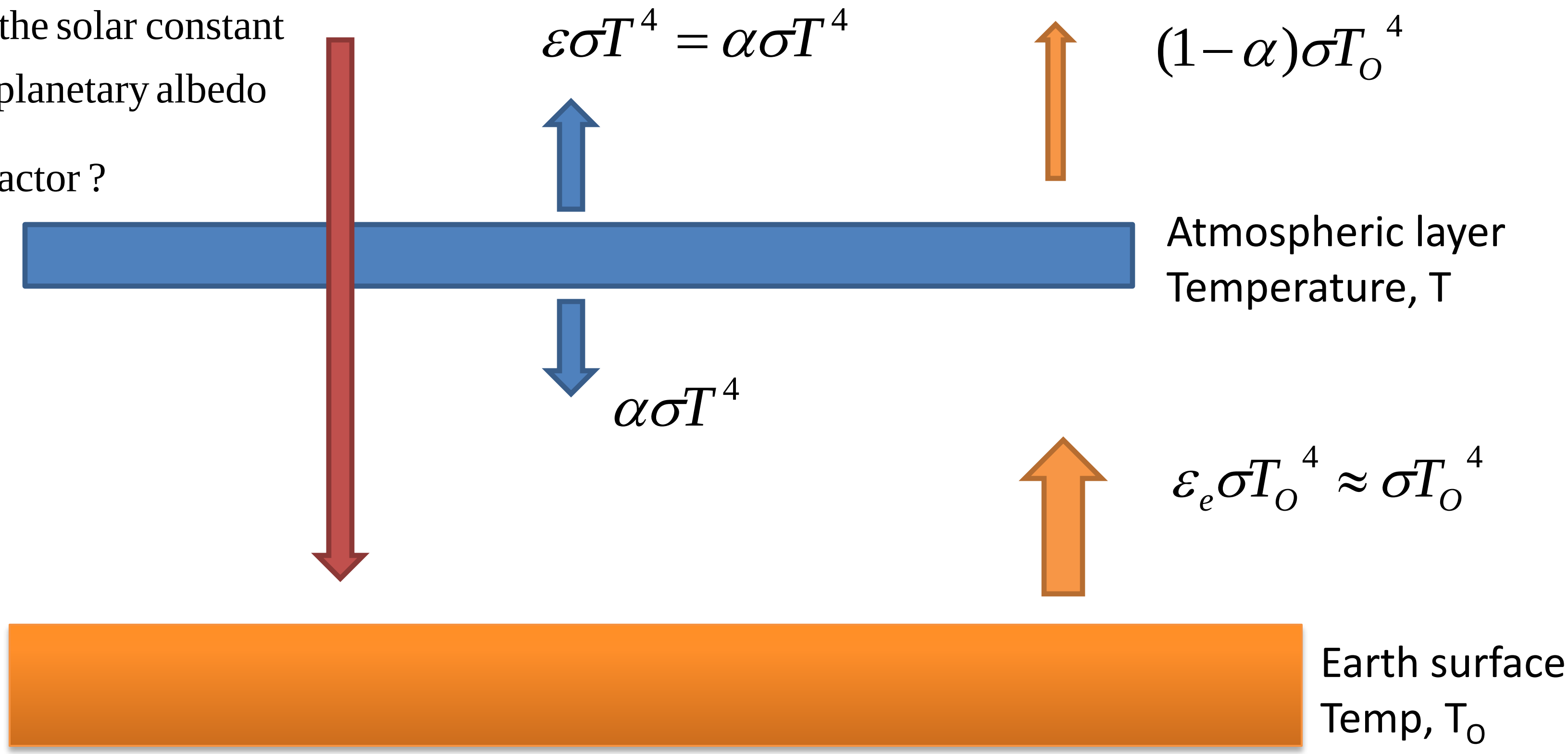
A simple greenhouse model

- Simple energy balance model using thermal radiation and one atmospheric layer
- Assume certain percentage of insolation is rejected *a* (planetary albedo) by the atmosphere, also assume blackbody emission from the earth surface (ε_e=1), and the atmospheric absorptivity is the same as its emissivity α=ε (kirchhoff's law)

$$\frac{1}{4}F_S(1-a),$$

where F_S is the solar constant and a is the planetary albedo

Why the $\frac{1}{4}$ factor?



Energy Balance

Energy balance of the earth and the atmosphere :

Incoming solar irradiation = escaped earth emission + outward atmospheric emission

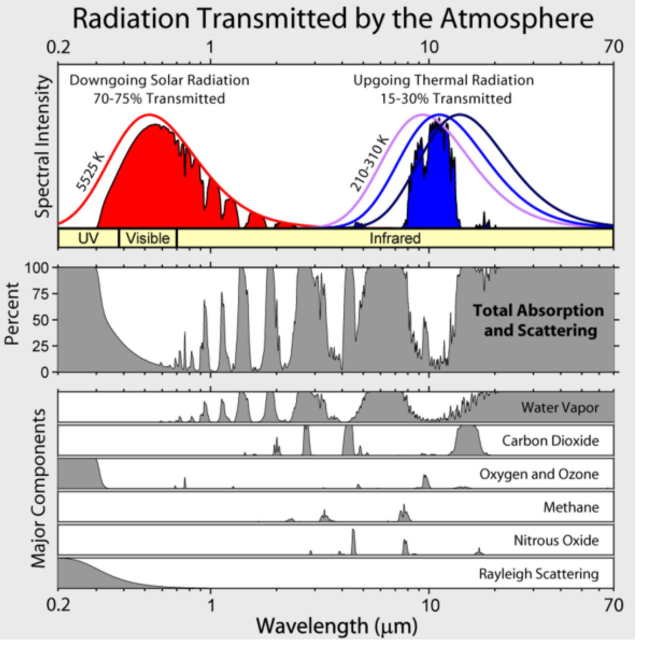
$$\frac{1}{4}F_S(1-a) = (1-\alpha)\sigma T_O^4 + \alpha\sigma T^4$$

Energy balance of the atmospheric layer only

Absorbed earth emission = outward & inward atmospheric emission

$$\alpha\sigma \mathrm{T}_\mathrm{O}^4 = 2\alpha\sigma T^4 \Rightarrow T_O = 2^{\frac{1}{4}}T$$

$$\frac{1}{4}F_S(1-a) = (1-\alpha)\sigma T_O^4 + \alpha\sigma(2^{-\frac{1}{4}}T_O)^4 = \left(1-\frac{\alpha}{2}\right)\sigma T_O^4$$



From data, 15 - 30% of earth emission is transmitted,

$\alpha = 0.775$

$$T_O = \left[\frac{F_S(1-a)}{4\sigma\left(1-\frac{\alpha}{2}\right)}\right]^{\frac{1}{4}}, \text{ take } a = 0.3,\ \mathrm{F_S} = 1370\mathrm{W/m^2} \Rightarrow \alpha = 0.775 \Rightarrow T_O = 288K$$

Radiative Forcing

- The atmosphere reaches a thermal balance between incoming, reflected solar irradiation and outgoing terrestrial radiation (a combination of earth and atmospheric emission, etc..)

$$F_{in} = F_{out} \Rightarrow \frac{F_S}{4} = \frac{aF_S}{4} + \left(1 - \frac{\alpha}{2}\right)\sigma T_O^4$$

- However, if excessive amount of GHGs is added, then the balance will be broken and the temperature will rise (greenhouse warming effect). One can consider this change as a heat flux imbalance, ΔF (radiative forcing) measured in W/m^2

$F_{out} \Rightarrow F_{out} - \Delta F$, an effective decrease of outward heat flux by trapping heat. This can be estimated to model global warming effect due to anthropogenic GHGs release

Radiative Forcing

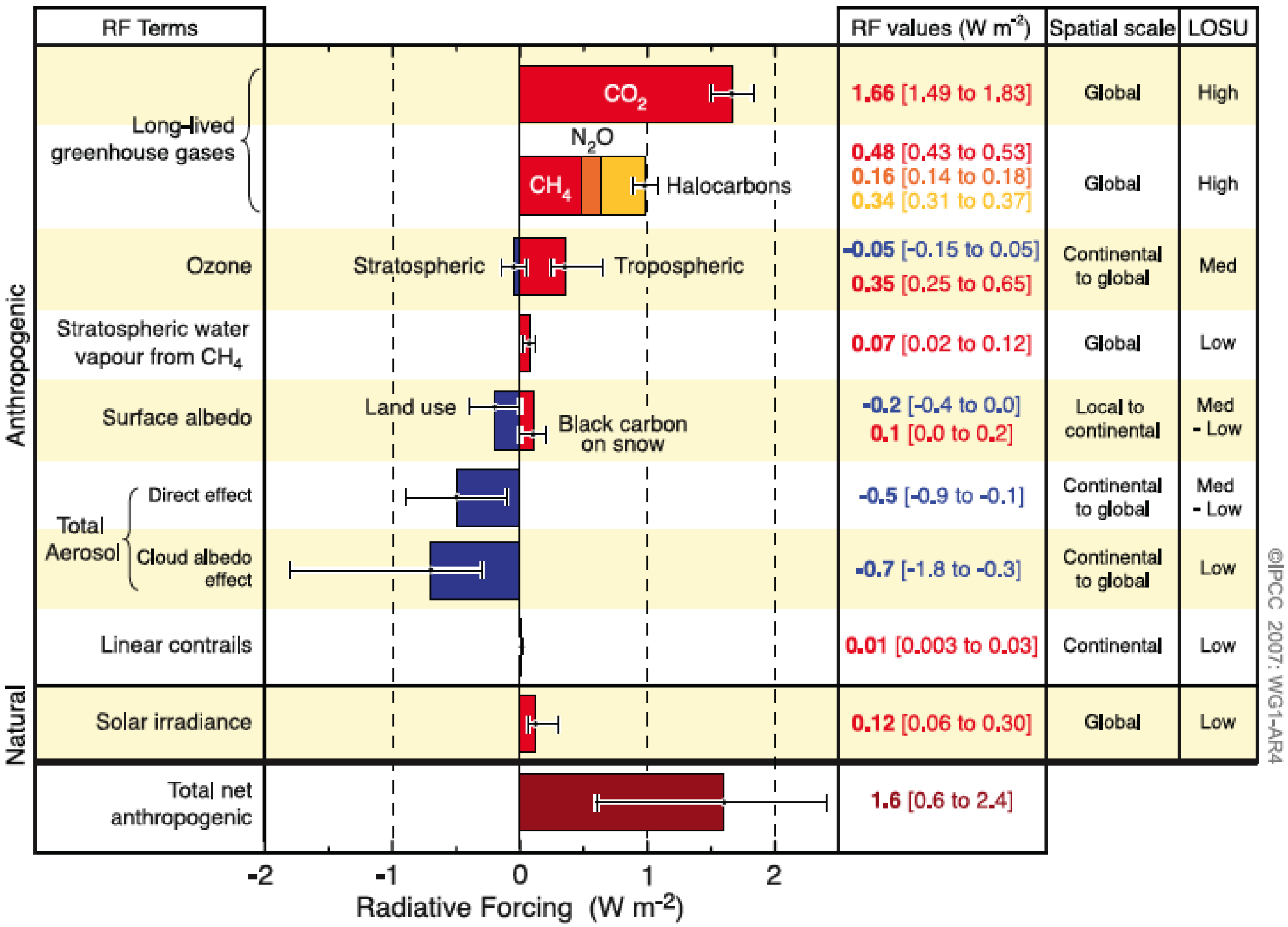


Figure SPM.2. *Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}*

Global Warming Potential (GWP)

- GWP is a measure of the relative importance of a given mass of GHG is estimated to contribute to global warming as compared with the same mass of CO_2. The GWP is calculated over a specific time interval as defined below:

$$GWP_X = \frac{\int_0^T \Delta F_{X\,(1kg)}\,dt}{\int_0^T \Delta F_{CO_2\,(1kg)}\,dt}$$, where gas X is injected into the atmosphere at time 0 and the effect is integrated over a time period of T

Gas	Lifetime (yr)	20Yr	100Yr	500Yr
CO_2	100	1	1	1
CH_4	10	62	25	8
N_2O	120	290	320	180
CFC-12	102	7900	8500	4200
HCFC-123	1.4	300	93	29
SF_6	3200	16500	24900	36500

Radiative Forcing and Surface Temperature

- Use the single layer model by assuming a certain amount of GHG is injected into the atmosphere. As a result, it leads to an increase of the atmospheric absorptivity from α to Δα, and an increase of the surface temperature from T_O to ΔT_O after the system reaches a new equilibrium. The new balance equation:

$$\frac{1}{4}F_S(1-a) = \left(1-\frac{\alpha+\Delta\alpha}{2}\right)\sigma\left(T_O+\Delta T_O\right)^4, \quad \left(T_O+\Delta T_O\right)^4 \approx T_O^4 + 4T_O^3\Delta T_O \text{ for small perturabtion}$$

$$\Rightarrow \Delta \mathrm{T_O} = \frac{T_O\Delta\alpha}{8\left(1-\frac{\alpha}{2}\right)} \Rightarrow \Delta T_O = \lambda\Delta F, \text{ where } \lambda \text{ is the climate sensitivity parameter}$$

The difference in radiative force is:

$$\Delta F = \left(1-\frac{\alpha}{2}\right)\sigma T_O^4 - \left(1-\frac{\alpha+\Delta\alpha}{2}\right)\sigma T_O^4 = \frac{\Delta\alpha}{2}\sigma T_O^4 \Rightarrow \lambda = \frac{1}{4\left(1-\frac{\alpha}{2}\right)\sigma T_O^3} = 0.3\left(\frac{m^2K}{W}\right)$$

- For a total of net anthropogenic radiative forcing of 1.5 W/m^2 the forcing will lead to 0.45°C warming. This is a little bit lower than the observed 1°C change. It is reasonable since we neglect the positive feedback effect.