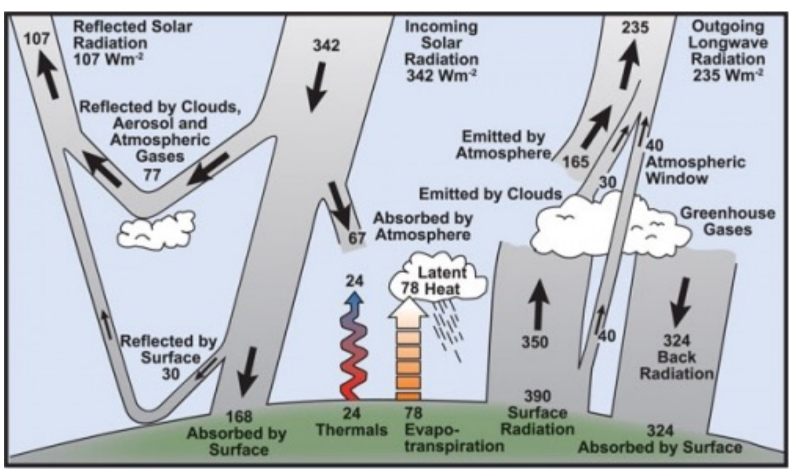
Introduction to Earth System

Energy Balance Model &
Greenhouse effect

1

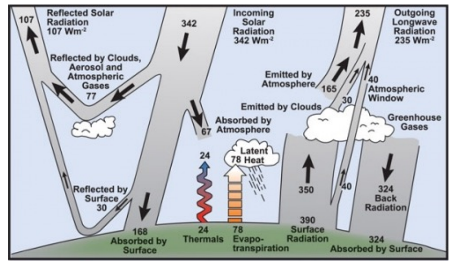
Energy balance



2

Energy balance

- Q. Earth's surface temperature generally depends on which factors?



1. Solar flux
2. Earth's reflectivity, called albedo
3. Heat exchanges with the atmosphere
4. Energy radiated by the surface
5. The amount of warming provided by the atmosphere

EBM: Energy Balance Model

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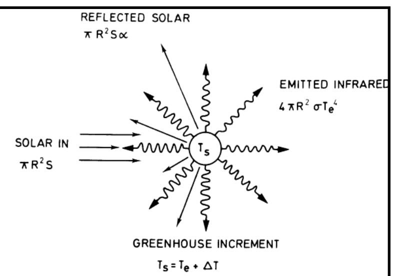
0-D EBM

$$(1-\alpha)S/4 = \sigma T_e^4$$



- S: Solar constant, for the Earth, S=1370W/m^2
- α: planetary albedo (~0.3)
- σ: Stefan-Boltzman constant (5.6696E-8 W/m^{2}K^4).

→ T_e=-18ºC

- If in the atmosphere, there are GHGs → surface temperature $T_s > T_e$.
- $T_s = T_e + \Delta T$ or $\varepsilon\sigma T_s^4 = \sigma T_e^4$

ΔT: greenhouse increment

ε: planetary emissivity

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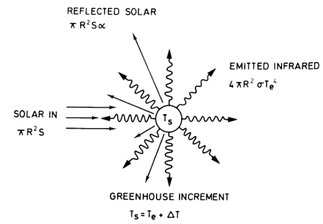
0-D EBM

- $T_s = T_e + \Delta T$

$$\varepsilon \sigma T_s^4 = \sigma T_e^4$$



- For the Earth, $\Delta T \sim 33K$. Let $\alpha=0.3$ → ? T_s
- Let $\varepsilon=0.6$ → ? T_s

Example

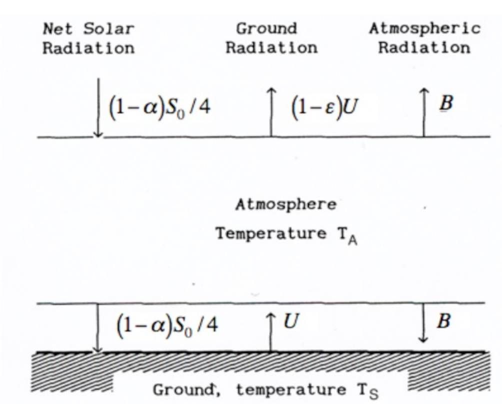
- Venus: measured $T_s \sim 730K$. $S=2619Wm^{-2}$, $\alpha=0.7$ → T_e=?

Te=242K.

ε replaces a very complex process → parameterization
The procedure to find ε so that T_s is the closest to the real value → tuning

The Greenhouse Effect

- In 0-D model (the Earth is considered as one point)→ **T_E=255K**
- <u>Case 1:</u> consider **the atm with 1 layer**, supposing the atm is transparent to shortwave radiation; and opaque to longwave radiation → ε≈1

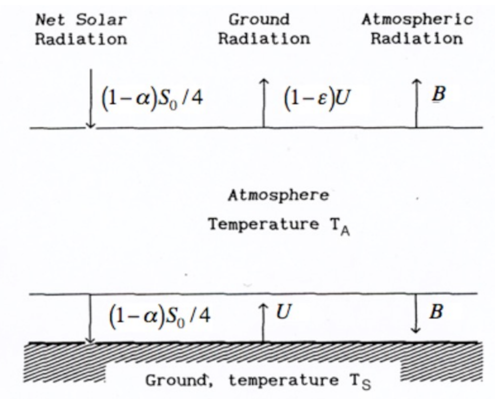


Write the energy balance equations at:

→ TOA
→ Atmosphere
→ Surface

The Greenhouse Effect

- ε≈1



At the TOA

$$\frac{S_0}{4}(1-\alpha) = B \equiv \sigma T_E^4 = \sigma T_A^4$$

For the atmosphere

$$U = \sigma T_S^4 = 2B = 2\sigma T_A^4$$

$$T_S = \sqrt[4]{2}T_E$$

T_E=255K → T_s=303K

→ T_S > 288K (observed value)
→ The presence of the atm raises the temperature of the Earth → greenhouse effect

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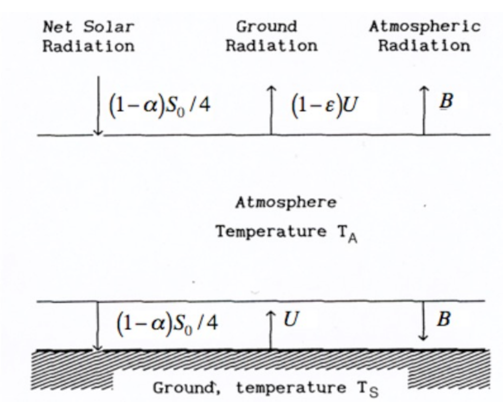
The Greenhouse Effect

- **Case 2:** Assume the atm is semi-grey→ ε<1

$$\frac{S_0}{4}(1-\alpha) = \sigma T_E^4$$



Write the energy balance equations at:

→ TOA
→ Atmosphere
→ Surface

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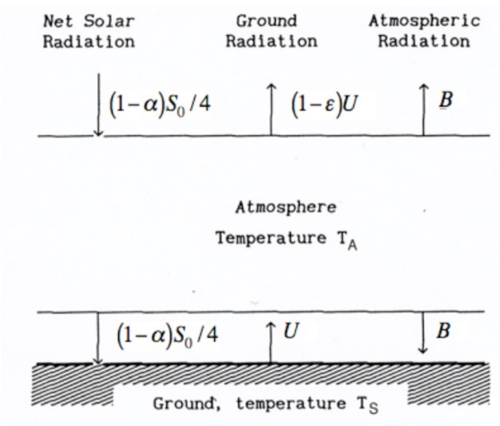
The Greenhouse Effect

According to the Kirchhoff's law, the atm emits energy at a rate B (upward and downward) given by:

$$B = \varepsilon \sigma T_A^4$$



At the surface

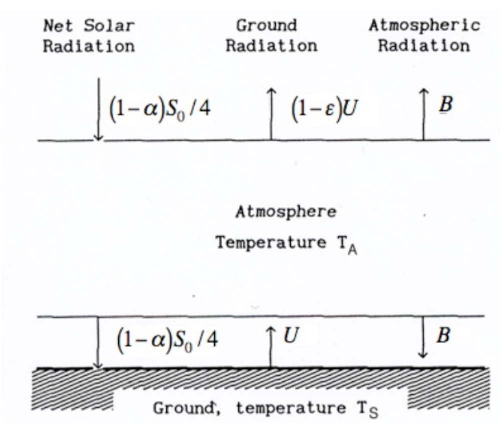
$$\frac{S_0}{4}(1-\alpha) + B = U$$

In the atm

$$2B = \varepsilon U$$

→ T_S=?, T_A=?

The Greenhouse Effect



$$\frac{S_0}{4}(1-\alpha) = \sigma T_E^4$$

$$B = \varepsilon \sigma T_A^4$$

$$\frac{S_0}{4}(1-\alpha) + B = U$$

$$2B = \varepsilon U$$

→

$$T_S = \left(\frac{2}{2-\varepsilon}\right)^{1/4} T_E$$

$$T_A = \left(\frac{1}{2-\varepsilon}\right)^{1/4} T_E$$

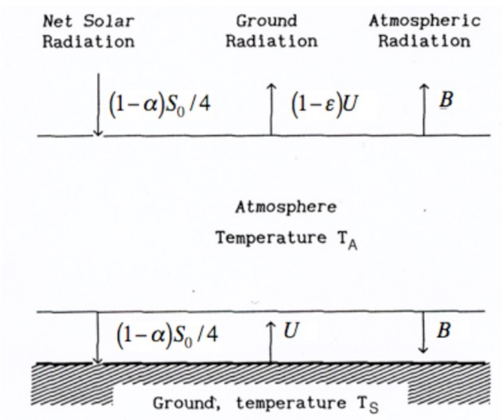
ε=0.78, α_p=0.3 → T_S=288K, T_A=242K

ε=0.9, α_p=0.3 → T_S=296K, T_A=249K

The Greenhouse Effect

The **strength of greenhouse effect** is measured through the so-called back radiation

$$F_{\downarrow} = B = \varepsilon\sigma T_A^4 = \frac{\varepsilon}{2-\varepsilon}\sigma T_E^4 \equiv \frac{\varepsilon}{2-\varepsilon}Q.$$



- ε increases → B increases → T_s increases
- The atm may radiate as much energy to the surface as the Sun

Exercise #1

- Atm of two layers
- Supposing the atm is transparent to shortwave radiation; and the atm layers are opaque to longwave radiation ($\varepsilon_1 = \varepsilon_2 = 1$).
- Surface is considered as a black body.
- The incoming radiation flux is S_0. The planetary albedo is α

a) Write the radiation balance equation at each layer;

b) Calculate surface temperature, and temperature at each atmospheric layer

Exercise #2

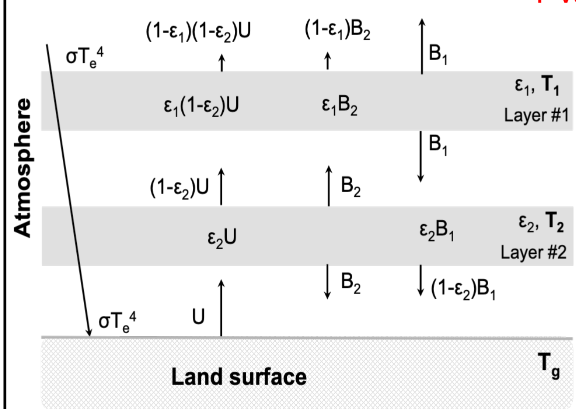
- Atm of two layers
- Supposing the atm is transparent to shortwave radiation; and the emissivity of each layer is ε_1 and ε_2, respectively.
- Surface is considered as a black body.
- The incoming radiation flux is S_0. The planetary albedo is α

a) Write the radiation balance equation at each layer;

b) Calculate surface temperature, and temperature at each atmospheric layer

? the radiation balance equation

? Variables of the model



At the surface

At Layer #2

At Layer #1

At TOA?

$$T_1 = \sqrt[4]{\frac{2-\varepsilon_2}{A}}\,T_e$$

$$T_2 = \sqrt[4]{\frac{2+\varepsilon_1\varepsilon_2-\varepsilon_1\varepsilon_2^2}{A}}\,T_e$$

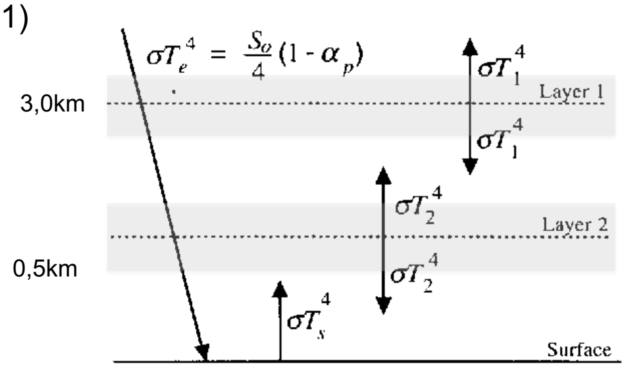
$$T_g = \sqrt[4]{\frac{4-\varepsilon_1\varepsilon_2}{A}}\,T_e$$

? $T_1<T_2<T_g$

$$A=4-2\varepsilon_1+2\varepsilon_1\varepsilon_2-2\varepsilon_1\varepsilon_2^2+\varepsilon_1\varepsilon_2^3-2\varepsilon_2$$

Vertical profile of Temperature

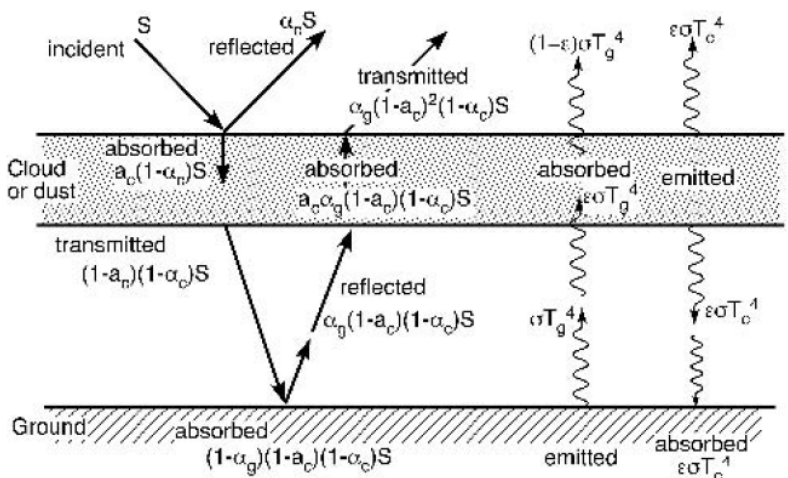
Atm. with 2 layers, transparent with shortwave, opaque with OLR (i.e. ε≈1)



→ $\sigma T_2^4 = 2\,\sigma T_1^4 = 2\,\sigma T_e^4$ → T_1=Te=255K, T2=303K, T_s=335K

Atm. with n layers → $T^4(n)=\tau_{TOTAL}(n)\, T_e^4$

Atm with cloud

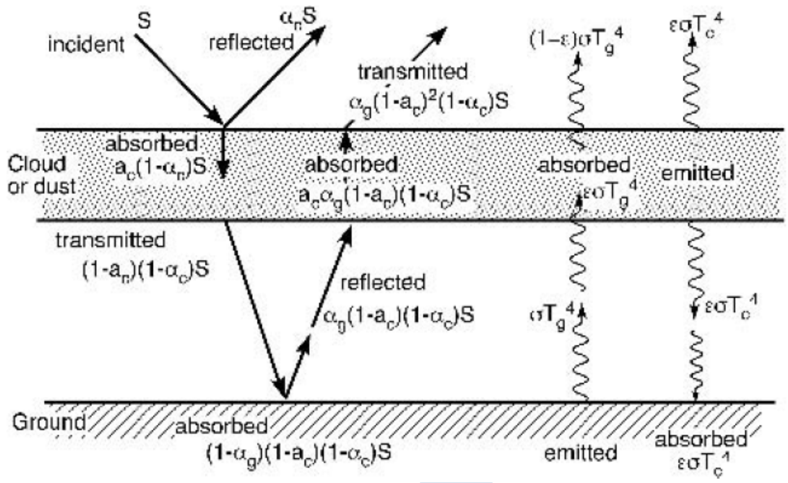


$$S = \alpha_c S + \alpha_g (1-a_c)^2 (1-\alpha_c) S + \varepsilon\sigma T_c^4 + (1-\varepsilon)\sigma T_g^4$$

$$a_c(1-\alpha_c)S + a_c\alpha_g(1-a_c)(1-\alpha_c)S + \varepsilon\sigma T_g^4 = 2\varepsilon\sigma T_c^4$$

$$(1-\alpha_g)(1-a_c)(1-\alpha_c)S + \varepsilon\sigma T_c^4 = \sigma T_g^4$$

Atm with cloud



$$\sigma T_g^4 = \frac{S(1-\alpha_c)}{(2-\varepsilon)}(2-a_c)$$

?

T_g vs. α_c
T_g vs. a_c
T_g vs. ε

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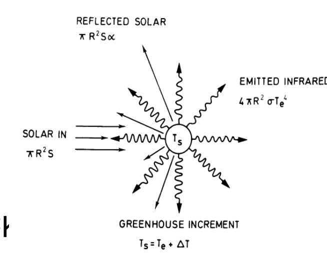
Practice #3.1 0-D EBM

$$(1-\alpha)S/4 = \sigma T_e^4$$



- S: Solar constant, for the Earth, S=1370W/m^2
- α: planetary albedo (~0.3)
- σ: Stefan-Boltzman constant (5.6696E-8 W/m^{2}K

Planet	Distance (AU - Astronomical Unit)	Albedo	Average surface temperature	Atmosphere
Venus	0.723	0.76	425 °C	95 Atm, 96% CO_2
Earth	1.000	0.32	15 °C	1 Atm, N_2, O_2, Trace H_2O, CO_2
Mars	1.524	0.16	-50 °C	0.02 Atm, 95% CO_2
Europa (a moon of Jupiter)	5.203	0.64	-145 °C	no atmosphere

Write a program to:

1. Estimate the incoming solar flux for those planets
2. Estimate their blackbody equivalent temperature
3. Plot: Te versus Solar fluxes → comment on the obtained results

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Practice #3.2 0-D EBM (cont.)

Given the solar constant of 1368 W/m^2, σ=5,67 × 10^{-8} W/m^2K^4 is the Stefan-Boltzmann constant. α is the planetary albedo

- Given the outgoing longwave radiation of the planet by $\varepsilon\sigma T_s^4$, where ε is the emissivity of the atmosphere , T_s is the surface temperature.

1. α=0,32 , write a python program to plot the dependence of T_s on ε
2. ε=0.66, write a python program to plot the dependence of T_s on α
3. * Write a python program to plot the dependence of T_s on both α and ε