Ocean-Atmosphere System I: Global Heat Budget

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General Physical Oceanography

MAR 555

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MAR 555 Lecture 1: How Is the Ocean Driven?

The ocean and atmosphere are coupled together to form a closed system. The energy to drive this system is from

the sun

The earth is a rotating system, so that the motion on the earth is affected by

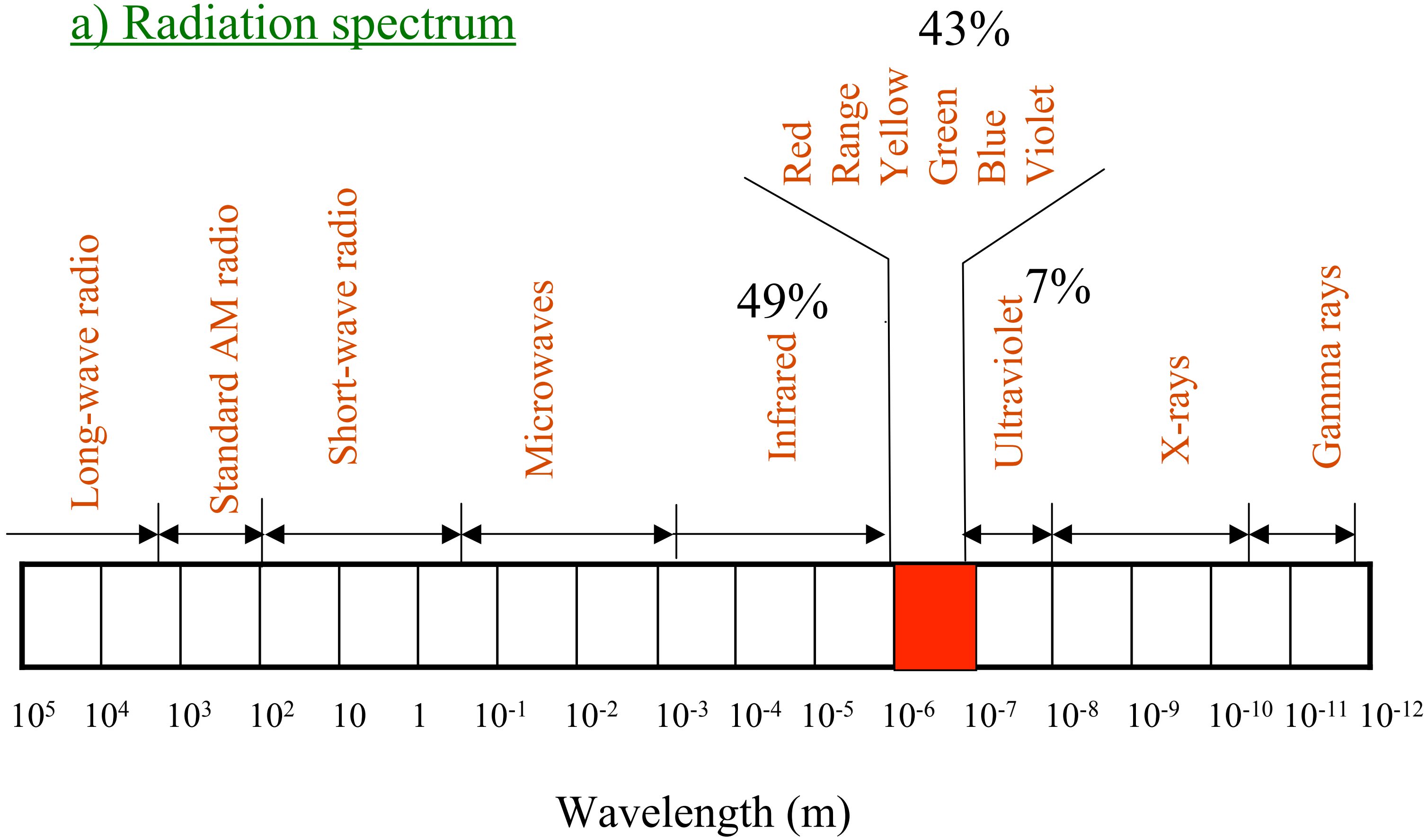
The Coriolis force

resulting from the movement of the fluid relative to the earth.

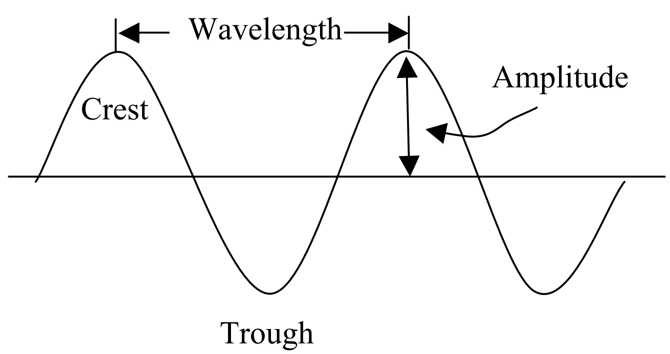
QS. 1: How does the earth receive energy from the sun and how can an equilibrium state of the heat budget be reached?

To answer this question, one must first understand the heat budget of the earth.

a) Radiation spectrum



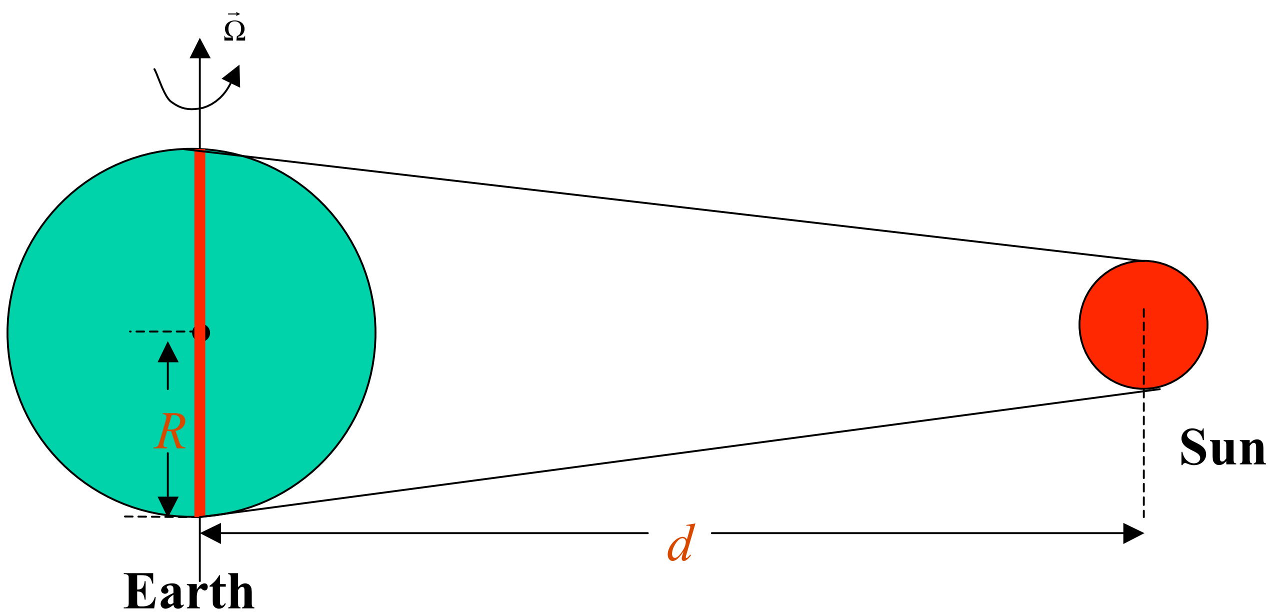
The wavelength of the solar waves: 0.2-4 µm



b) The solar constant

Definition: The solar constant S is the average energy flux received from the sun at the mean orbital distance d between the sun and earth. Its value is

$$S = 1.376 \times 10^{3}\, W/\mathrm{m}^{2} = 1.376\mathrm{kW}/\mathrm{m}^{2}$$



Question: Assuming no incident energy is absorbed or reflected by the atmosphere, what is the average amount of solar energy received per unit area of the earth's surface per unit time?

1) The area of the section: πR^2

Total energy received from the sun on this section:

$$\pi R^2 S$$

2) The total area of the earth's surface: $4\pi R^2$

The averaged amount of solar energy received per unit area of the earth's surface per unit time:

$$\overline{Q}_s = \frac{\text{The total energy}}{\text{The area of the earth's surface}} = \frac{\pi R^2 S}{4\pi R^2} = \frac{S}{4}$$

Consider a real earth that is tilted,

$$\overline{Q}_s \propto S\cos^2\theta/\pi: \quad \begin{cases} S/\pi & \text{at equator} \\ 0 & \text{at the poles} \end{cases}$$

3) The albedo of the earth

Definition: The albedo $\bar{\alpha}$ is a reflected or scattered rate of the solar radiation. The albedo plays an important role in the heat budget.

If the incoming solar radiation is S/4 and it is reflected at a rate of $\bar{\alpha}$, then the averaged flux received actually by the earth is equal to

$$\frac{S}{4} - \bar{\alpha}\frac{S}{4} = (1-\bar{\alpha})\frac{S}{4}$$

$\bar{\alpha}$ varies with the amount of cloud and the coverage of ice and snow. In general:

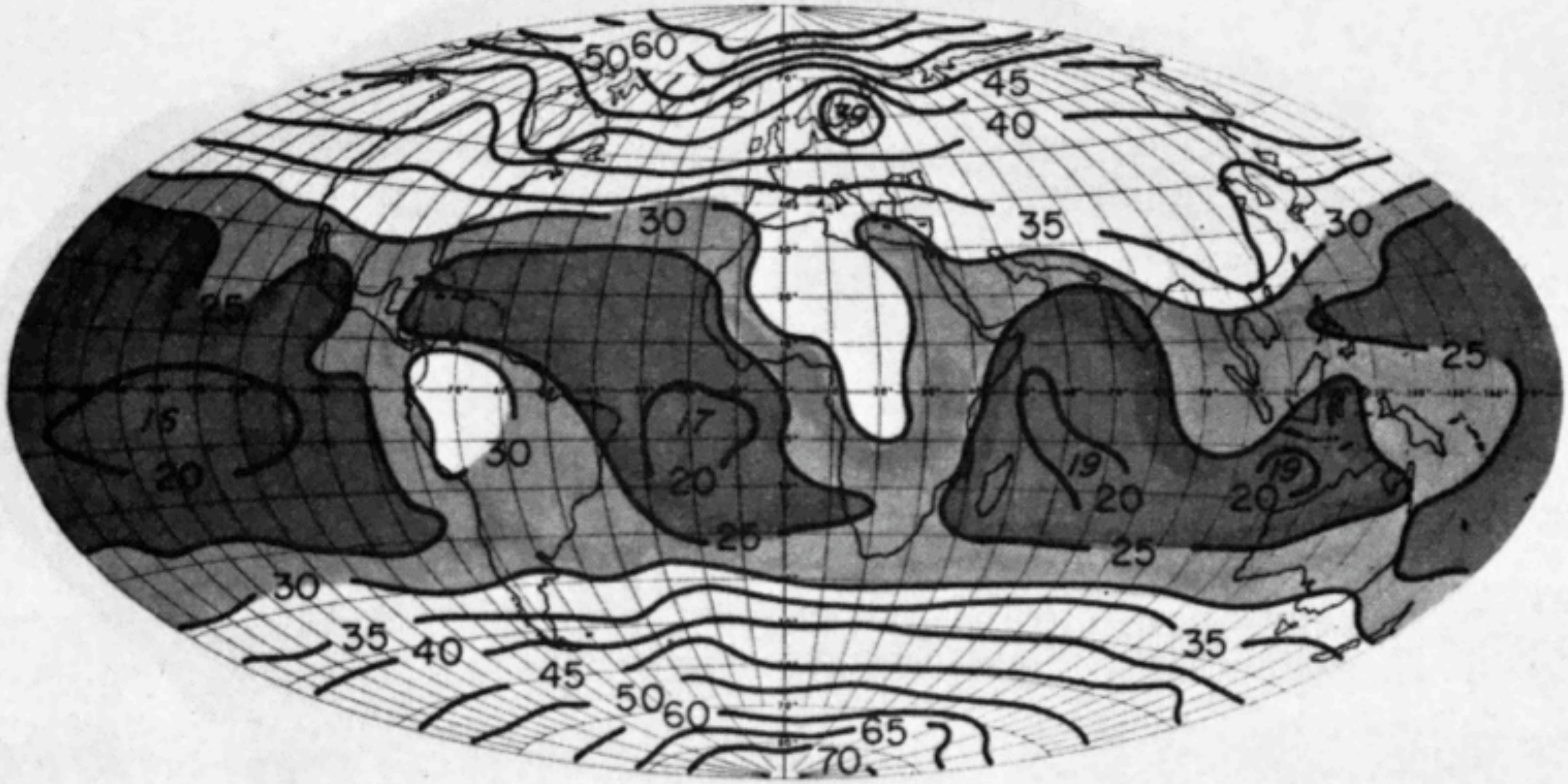
$$\bar{\alpha} = \begin{cases} 0.3 & \text{general} \\ 0.15 & \text{clear sky} \\ 0.6 & \text{overed fully by cloud} \end{cases}$$

Note: the effects of the coverage of ice or snow is similar to that of the clouds.

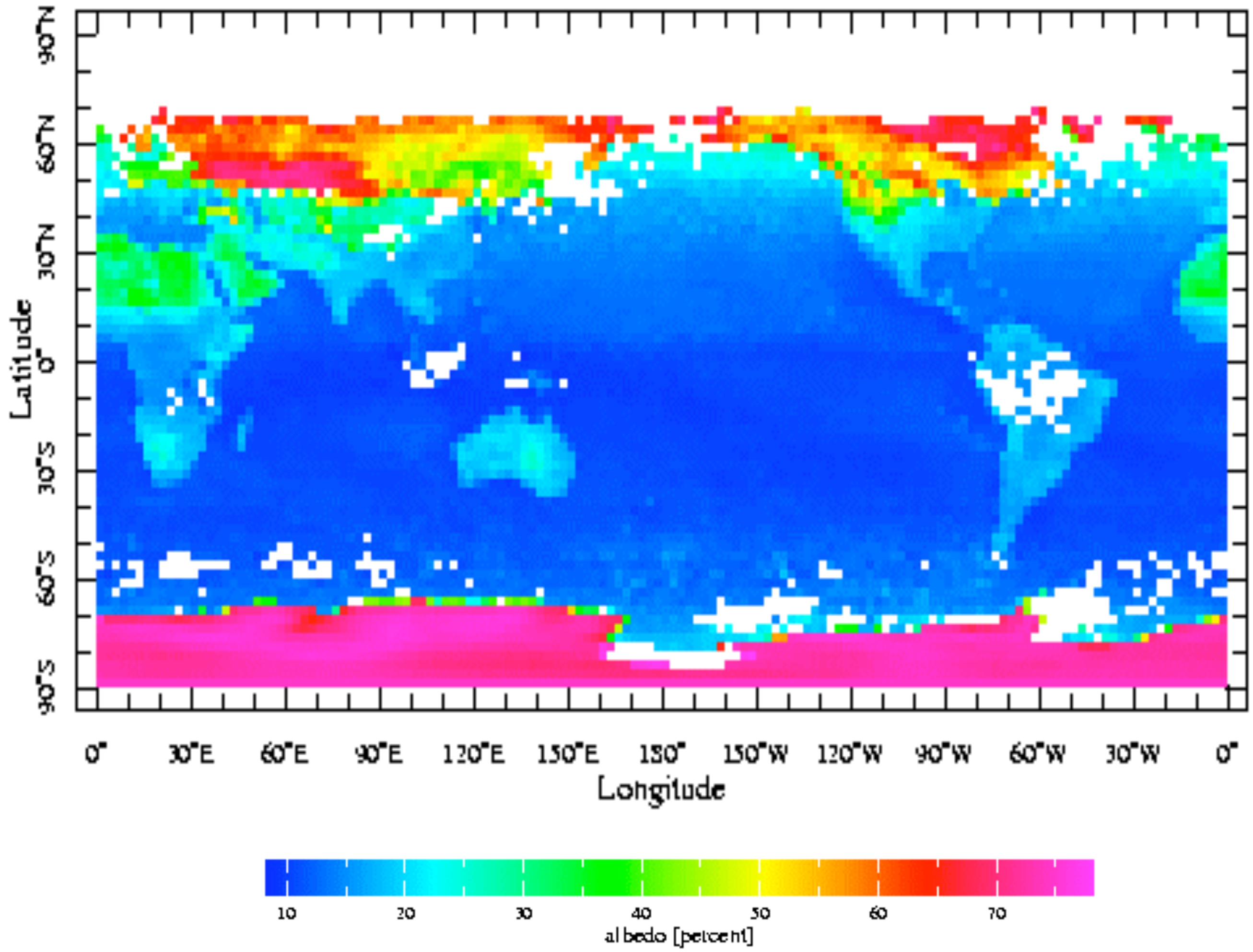
Estimated albedo over the ocean:

$$\bar{\alpha} = \begin{cases} 0.2-0.4 & -40^0 S \le \theta \le 40^0 N \\ 0.4 \text{ or larger} & \theta \le -40^0 S \\ 0.4 \text{ or larger} & \theta \ge 40^0 N \end{cases}$$

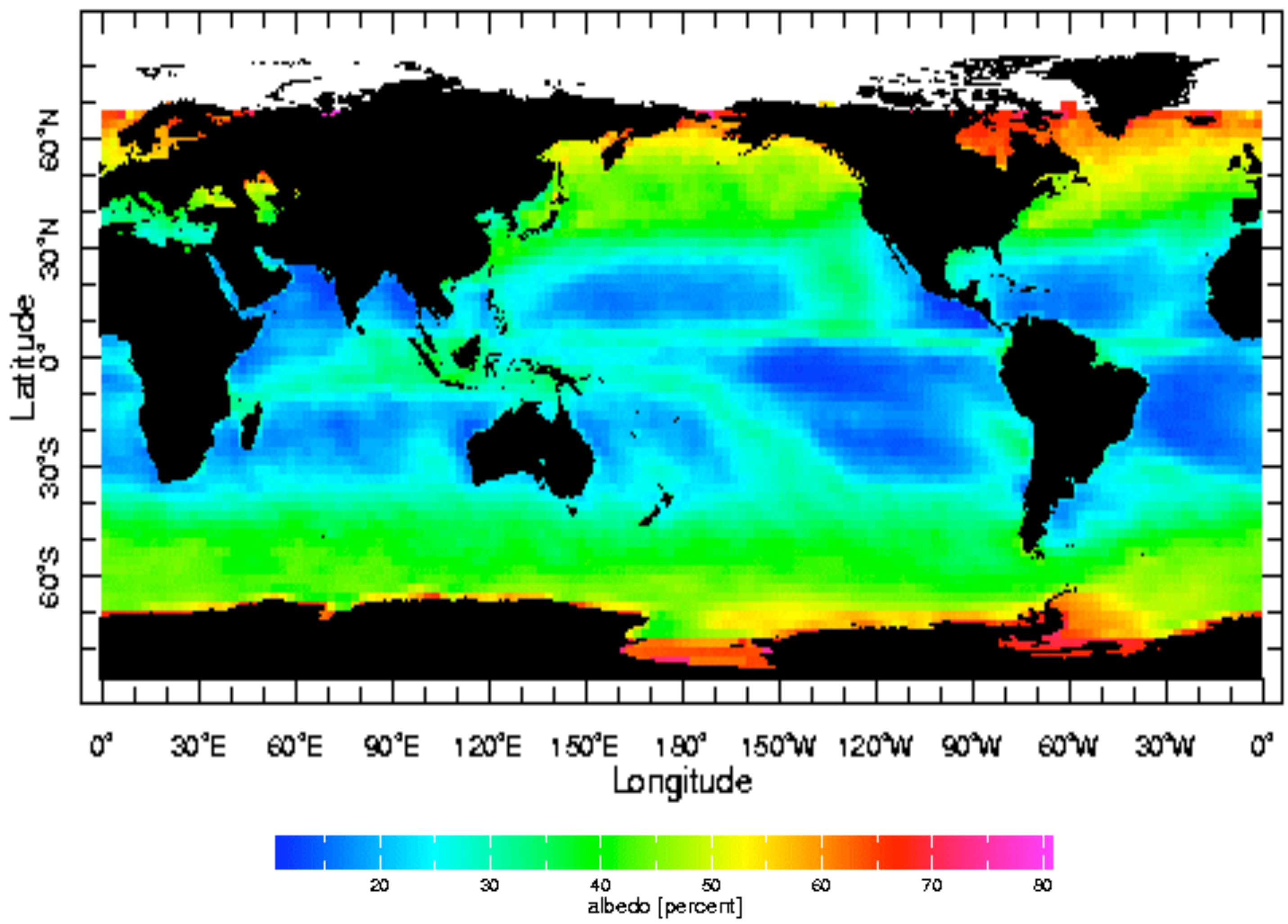
ANNUAL ALBEDO



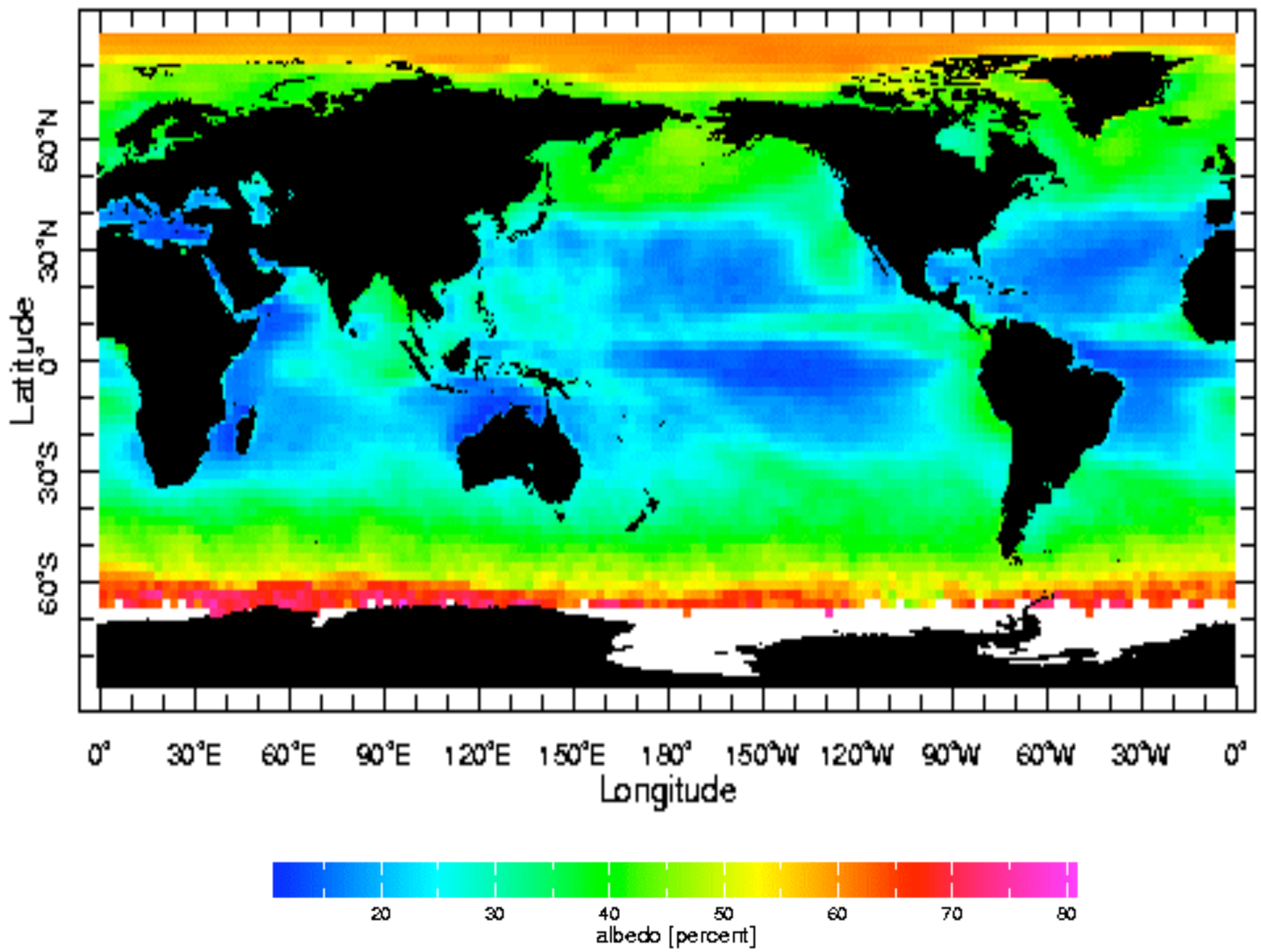
January (clear sky albedo)

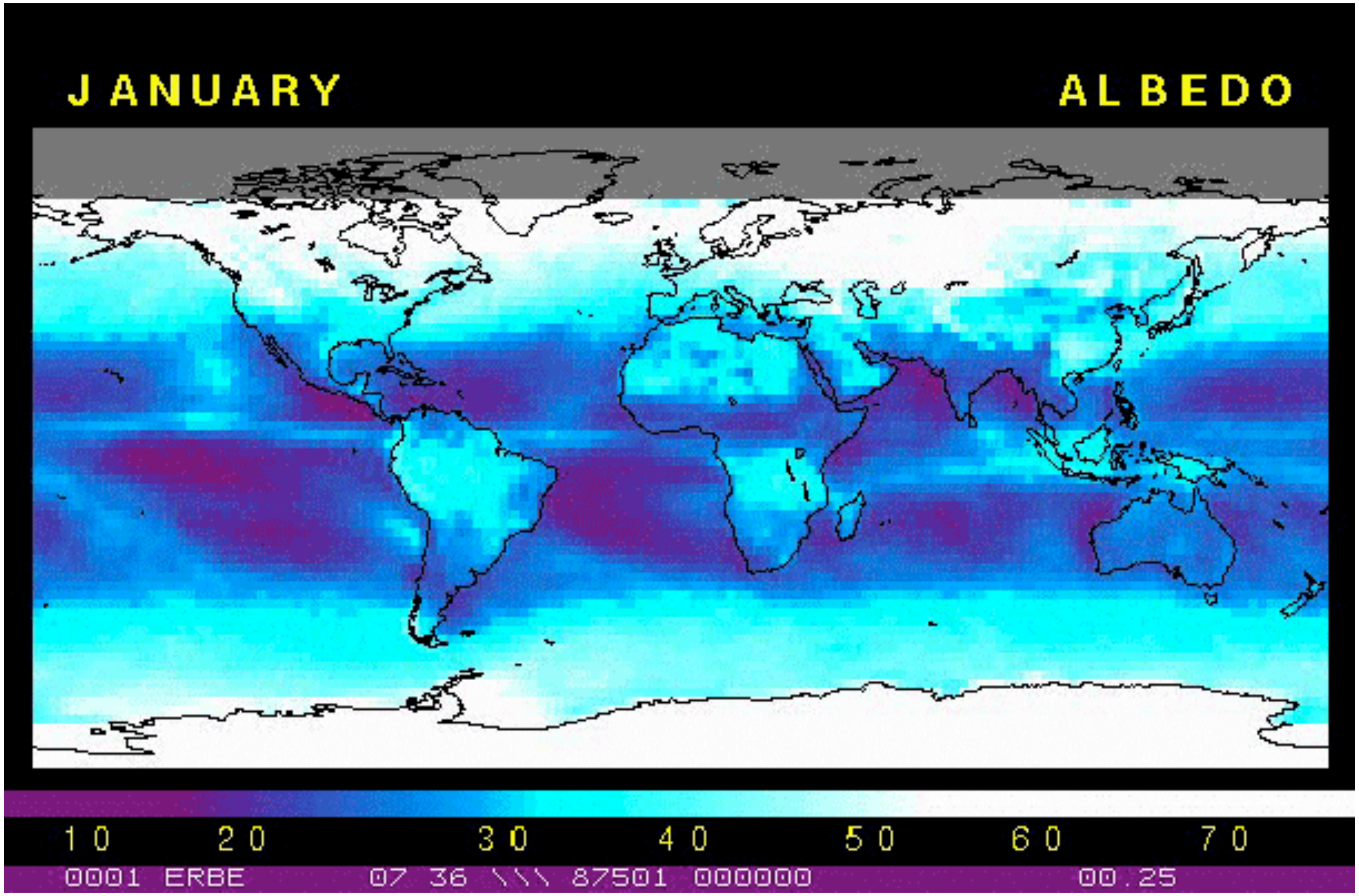


January albedo (with cloud cover)



August albedo (including cloud cover)





JANUARY
ALBEDO
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The greenhouse effect

$$S = 1.376 \times 10^3\, W/\mathrm{m}^2 = 1.376\mathrm{kW}/\mathrm{m}^2$$

Even with 30% reflection rate, a square meter of Earth can still receive 1 kW heat per unit time!

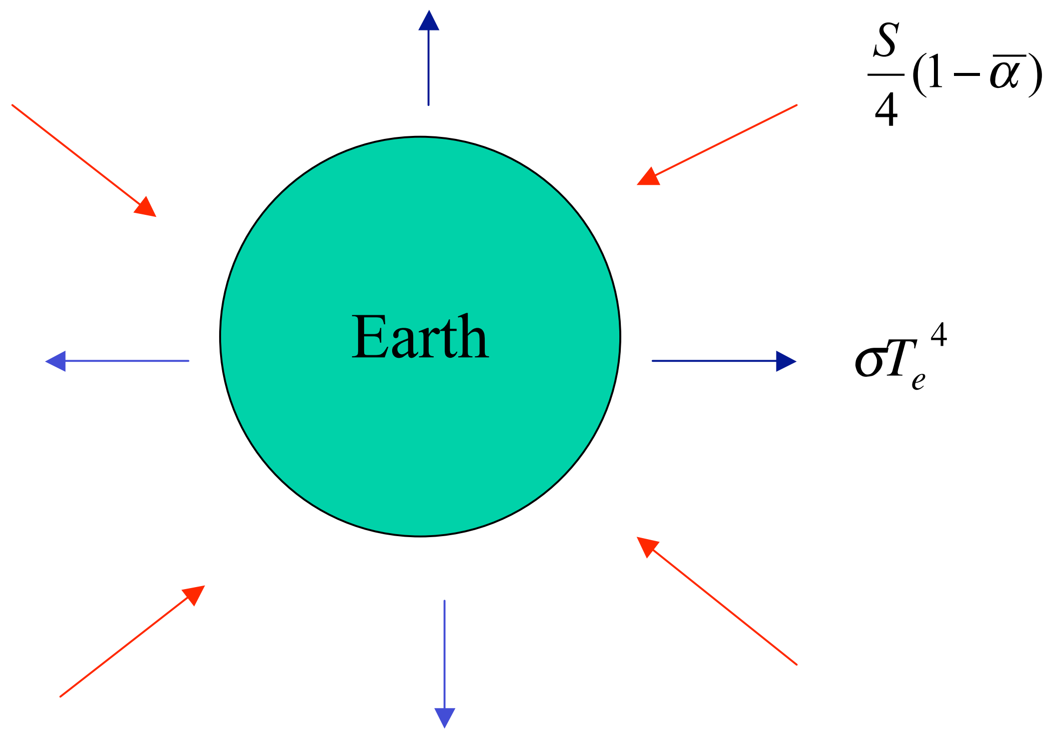
→ Like living on a microwave!

The temperature will increase until this incident solar energy is balanced by the outgoing reflection and radiation: when the energy budget attains an equilibrium state.

Question:

How is the solar energy budget balanced on the earth?

Example 1: The bare earth (no cloud cover)



Let T be the surface temperature of the earth and E is the amount of energy radiated per unit time from the earth, then

$$E = \sigma T^4$$

where σ is the Stenfan-Boltman constant, which is equal to

$$5.7 \times 10^{-8}\ \mathrm{W/m^2\ K^4}$$

The equilibrium state:

$$\frac{S}{4}(1-\overline{\alpha}) = \sigma T^4 \longrightarrow T = \sqrt[4]{\frac{1}{4\sigma}(1-\overline{\alpha})S}$$

Let $S = 1.376\,\mathrm{kW/m^2}, \quad \overline{\alpha} = 0.3, \sigma = 5.7\times10^{-8}\,\mathrm{W/m^2K^4}$

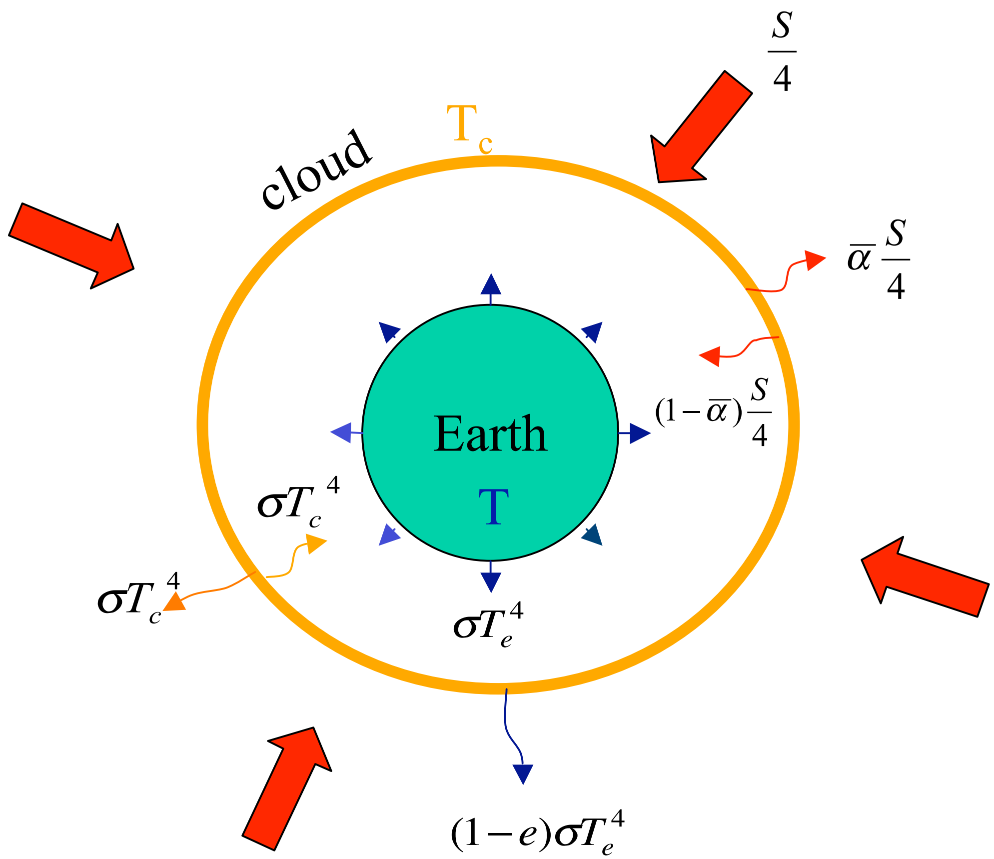
$$\boxed{T \cong 225\mathrm{K} = -18^{\mathrm{o}}\,\mathrm{C}}$$

If we include the variation of *S* with latitude, we would get

$$T = \begin{cases} 270K = -3^o C & \text{at equator} \\ 170K = -123^o C & \text{at south pole} \\ 150K = -103^o C & \text{at north pole} \end{cases}$$

Too cold!

Example 2: cloud-covered earth



Letting e be the fraction of the radiation absorbed by the clouds, we can derive the energy balance equation in the inner and outer sides of the cloud layer

a) Outer: $$\frac{S}{4} = \bar{\alpha}\frac{S}{4} + \sigma T_c^4 + (1-e)\sigma T^4$$

b) Inner: $$\frac{1-\bar{\alpha}}{4} S + \sigma T_c^4 = \sigma T^4$$

Adding (a) and (b) yields:

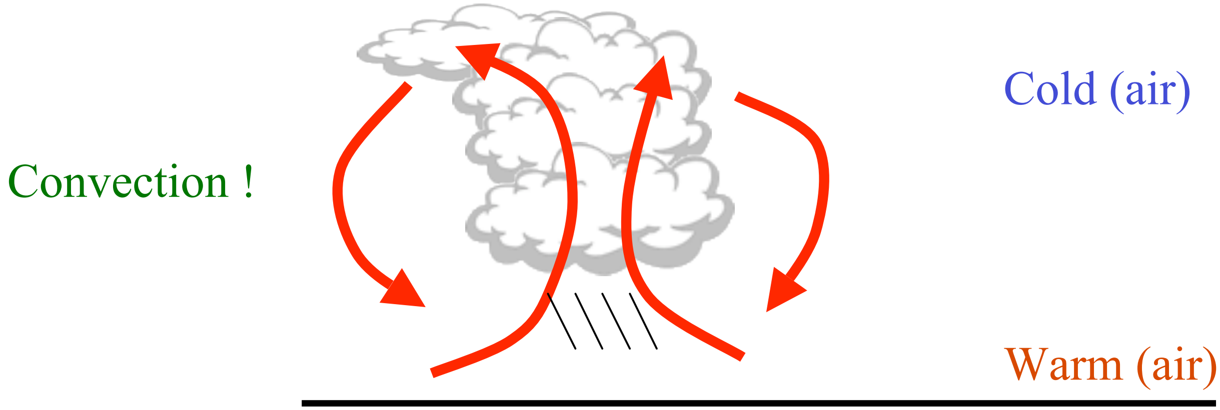
$$2\left(\frac{1-\bar{\alpha}}{4}\right) S = (2-e)\sigma T^4 \longrightarrow T = \sqrt[4]{\left(\frac{1-\bar{\alpha}}{4}\right) S / (1-e/2)}$$

When e = 1 (the long-wave radiation from the earth is absorbed completely by the cloud),

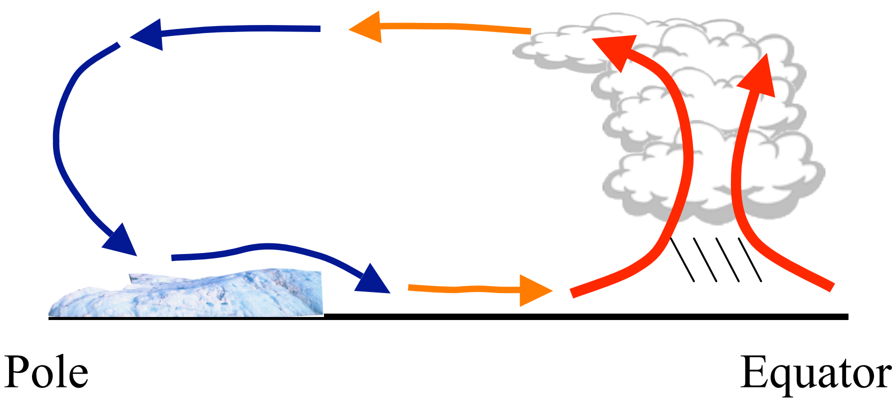
$$T = 303^o \text{ K} = 30^\text{o} \text{ C}$$

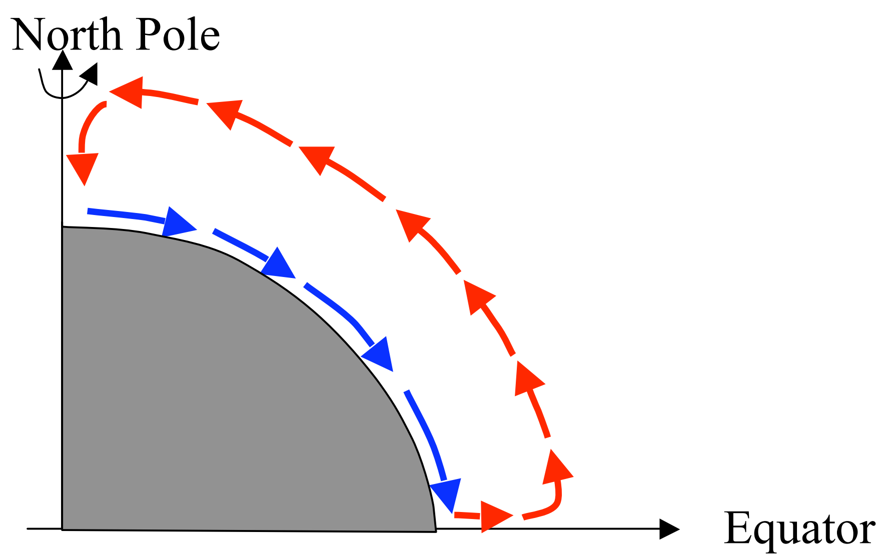
Therefore, the clouds effectively act like a greenhouse to absorb and retransmit outgoing radiation and ultimately increase the temperature of the earth!

On the real earth:



A single cell





Hadley Cells (1935)