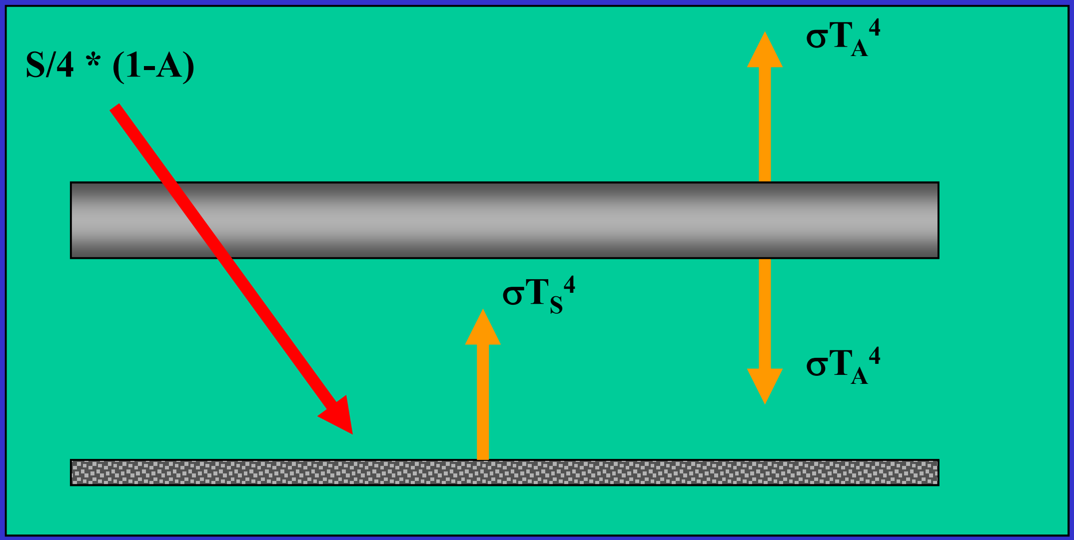
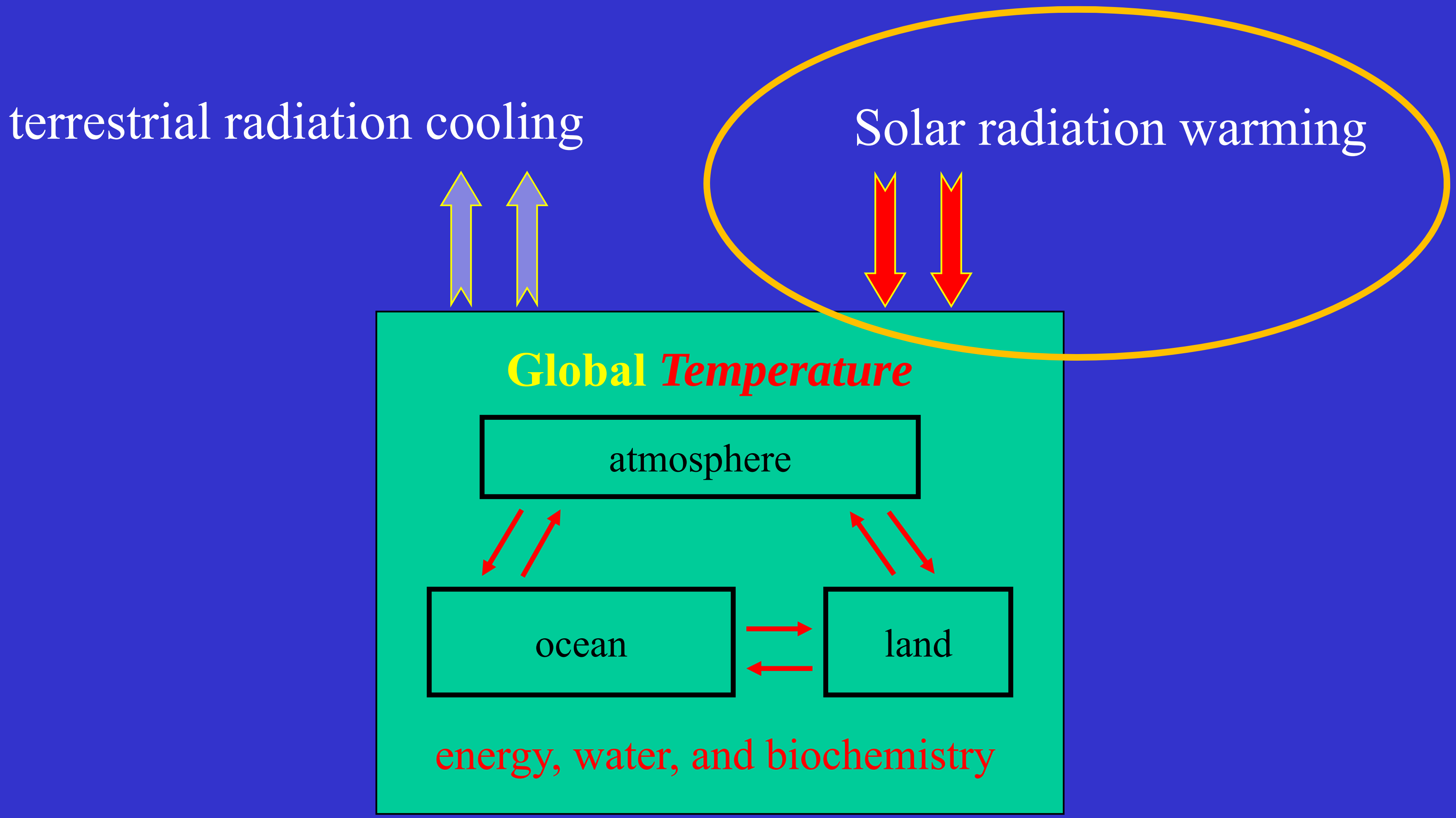
Lecture 4: Global Energy Balance



- Blackbody Radiation
- Layer Model
- Greenhouse Effect

Global *Energy* Balance



Solar Flux and Flux Density

- Solar Luminosity (***L***)

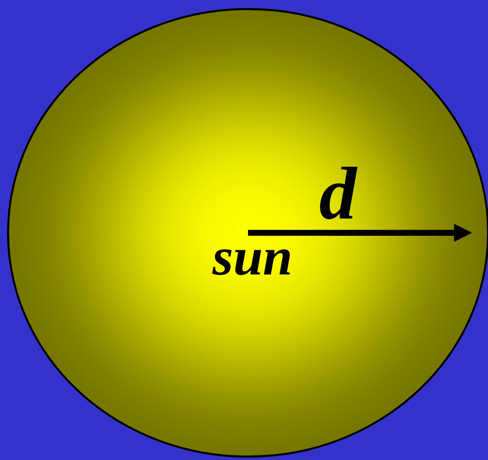
  the constant flux of energy put out by the sun

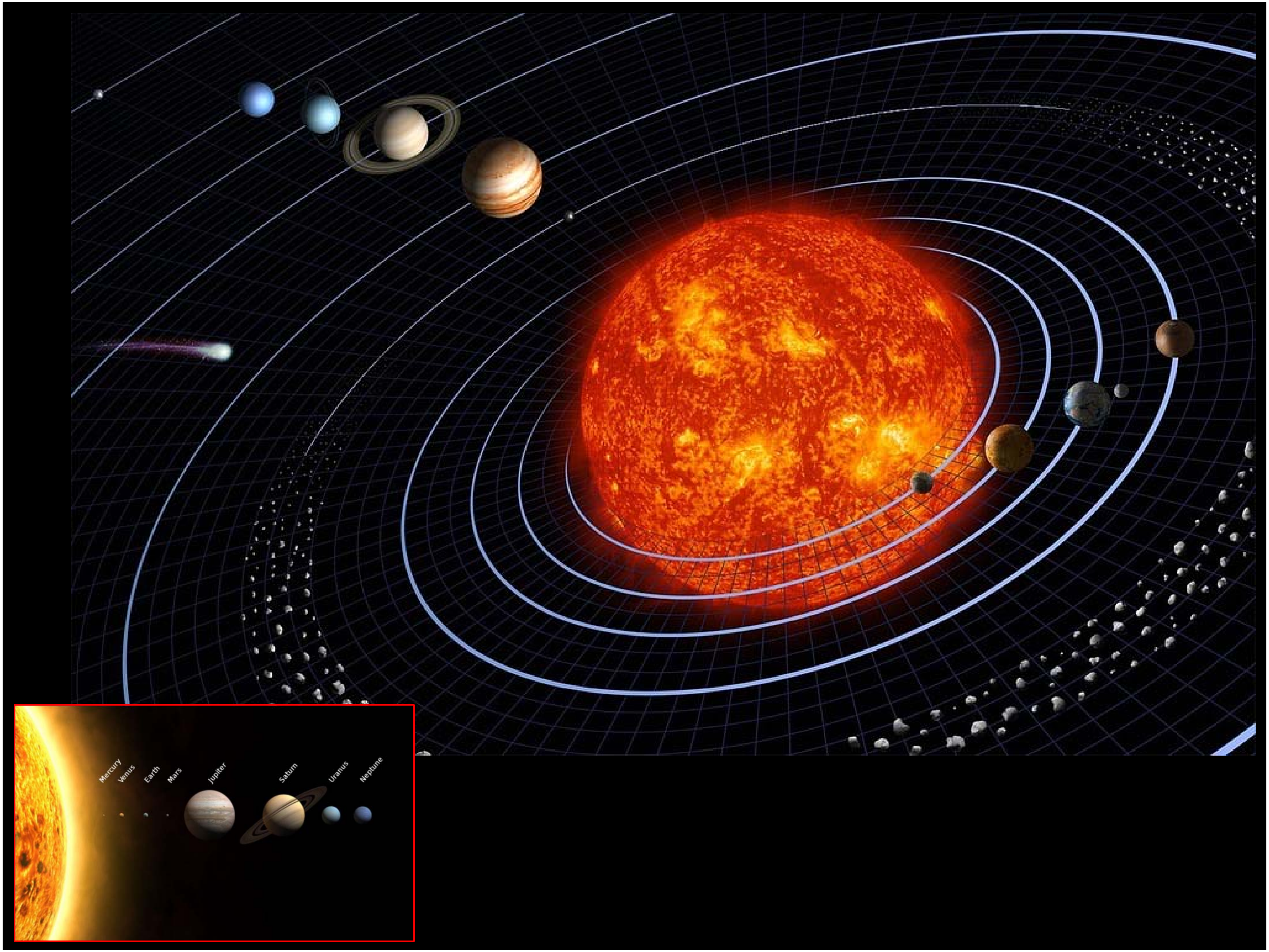
  $$L = 3.9 \times 10^{26} \text{ W}$$

- Solar Flux Density (S_d)

  the amount of solar energy per unit area on a sphere centered at the Sun with a distance ***d***

  $$S_d = L / (4 \pi d^2) \text{ W/m}^2$$




Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune

Solar Flux Density Reaching Earth

- Solar Constant (***S***)

  The solar energy density at the mean distance of Earth from the sun (1.5×10^{11} m)

$$\boldsymbol{S = L / (4 \pi d^2)}$$

$$\mathbf{= (3.9 \times 10^{26}\ W) / [4 \times 3.14 \times (1.5 \times 10^{11}\ m)^2]}$$

$$\mathbf{= 1370\ W/m^2}$$

Solar Energy Incident On the Earth

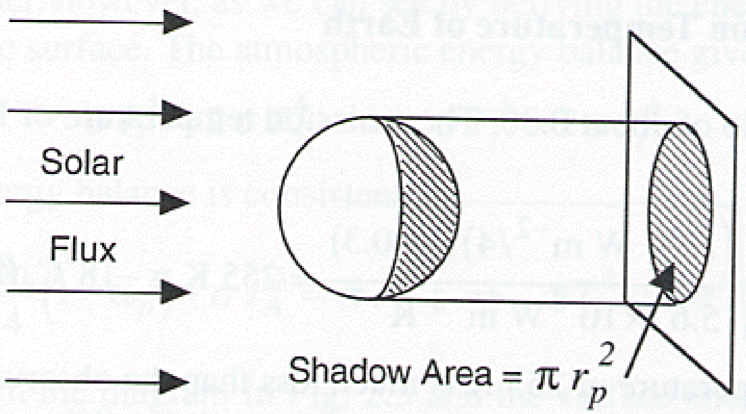
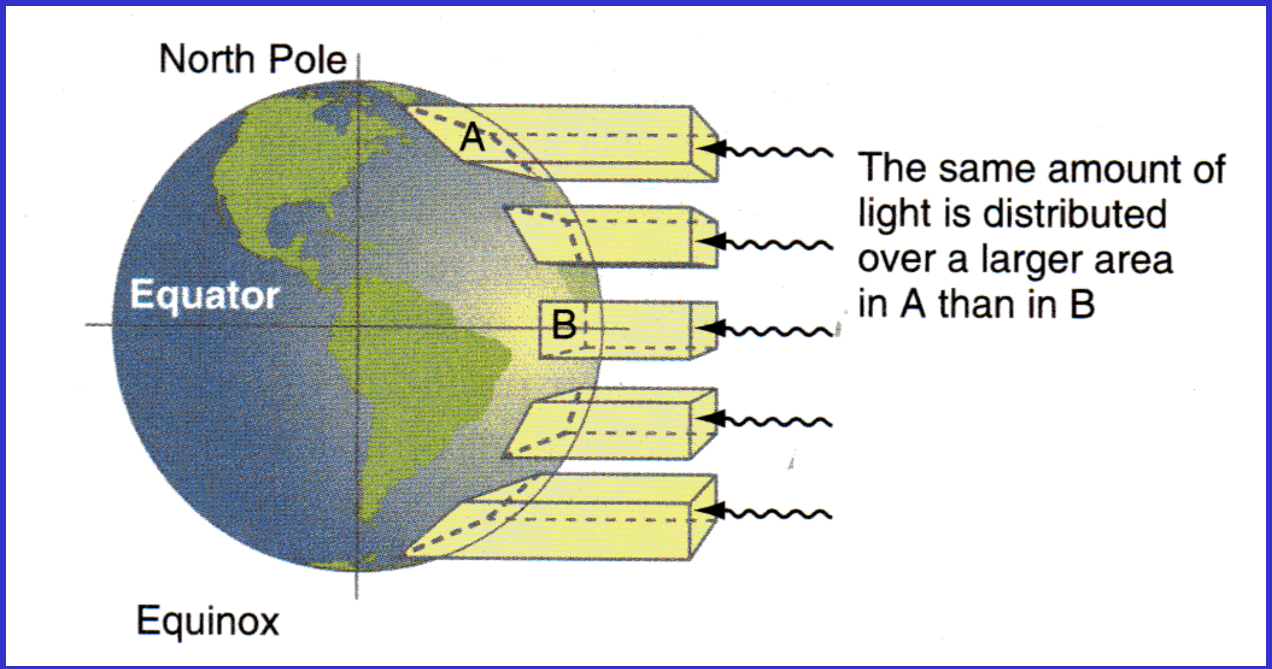


Fig. 2.2 Diagram showing the shadow area of a spherical planet.

- Solar energy incident on the Earth
  = total amount of solar energy **can be** absorbed by Earth
  = (Solar constant) x (Shadow Area)
  = $S * \pi R^2_{Earth}$

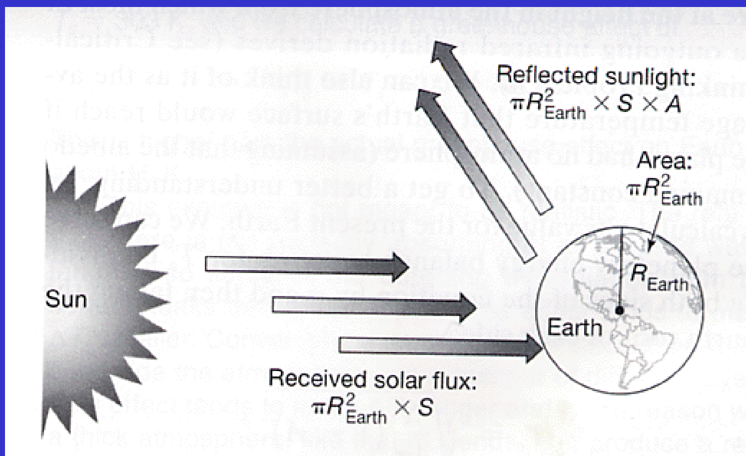
Zenith Angle and Insolation



(from *Meteorology: Understanding the Atmosphere*)

- The larger the solar zenith angle, the weaker the insolation, because the same amount of sunlight has to be spread over a larger area.

Solar Energy Absorbed by Earth



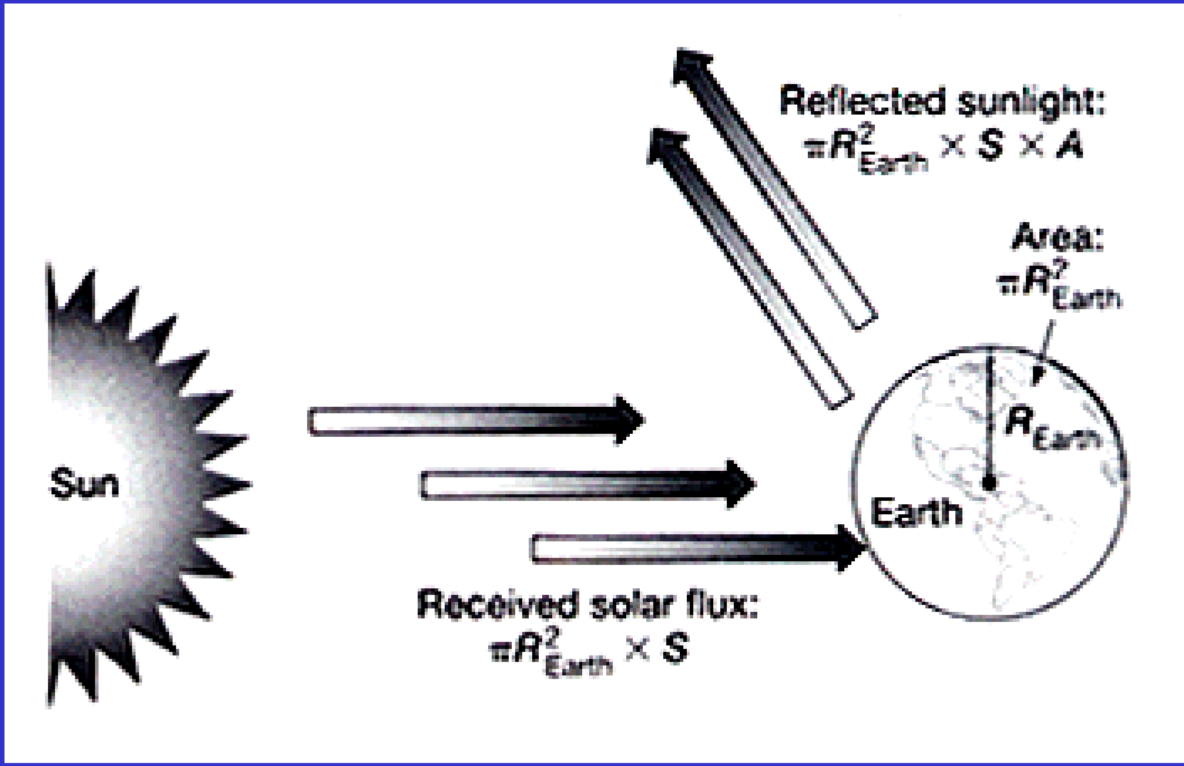
BOX FIGURE 3-1
The amount of sunlight received by and reflected by Earth.

(from *The Earth System*)

- **Solar Constant (S)**
  = solar flux density reaching the Earth
  = 1370 W/m^2
- **Solar energy incident on the Earth**
  = S x the "flat" area of the Earth
  = $S \times \pi R^2_{Earth}$
- **Solar energy absorbed by the Earth**
  = (received solar flux) – (reflected solar flux)
  = $S \pi R^2_{Earth} - S \pi R^2_{Earth} \times A$
  = $\mathbf{S \pi R^2_{Earth} \times (1-A)}$

A is the *planetary albedo* of the Earth, which is about 0.3.

Albedo = [Reflected] / [Incoming] Sunlight



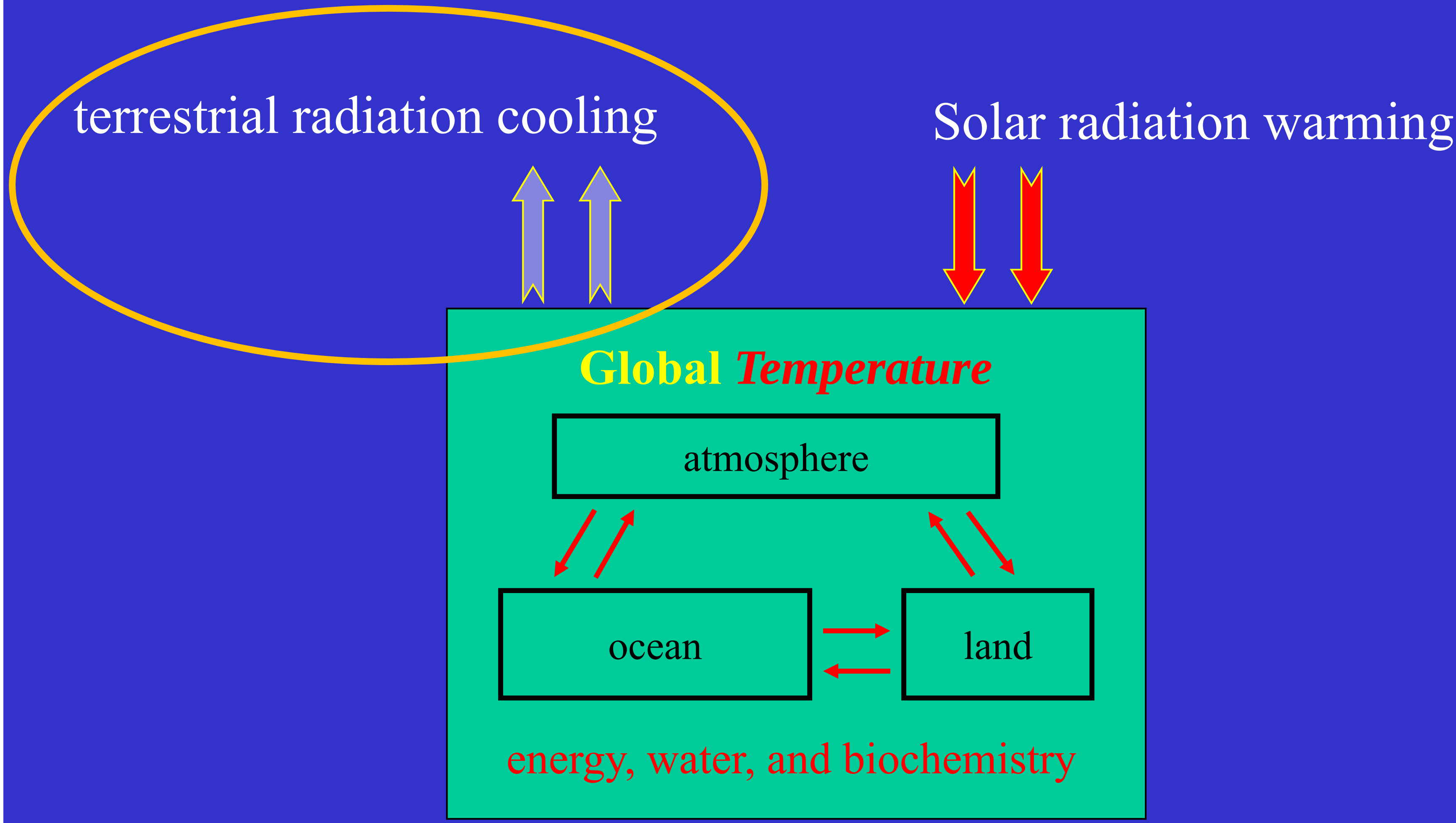
Albedo is the percentage of the sunlight that is reflected back to the space by the planet.

What Happens After the Earth Absorbs Solar Energy?

- The Earth warms up and has to emit radiative energy back to the space to reach a equilibrium condition.

- The radiation emitted by the Earth is called "terrestrial radiation" which is assumed to be like blackbody radiation.

Global *Energy* Balance



Blackbody Radiation

- Blackbody

  A blackbody is something that emits (or absorbs) electromagnetic radiation with 100% efficiency at all wavelength.

- Blackbody Radiation

  The amount of the radiation emitted by a blackbody depends on the absolute temperature of the blackbody.

Stefan-Boltzmann Law

$$E = \sigma T^4$$

E = radiation emitted in W/m^2

σ= 5.67 x 10^{-8} W/m^2 * K *sec

T = temperate (K ← ***Kelvin degree***)

- The single factor that determine how much energy is emitted by a blackbody is its temperature.
- The intensity of energy radiated by a blackbody increases according to the fourth power of its absolute temperature.
- This relationship is called the Stefan-Boltzmann Law.

Apply Stefan-Boltzmann Law To Sun and Earth

$$E = \sigma T^4$$

- **Sun's temperature is about 20 times higher than Earth's temperature.**
- **Sun emits about ______times more radiation per unit area than the Earth because Sun's temperature is about 20 times higher than Earth's temperature.**

(a) 20 (b) 400 (c) 8,000, (d) 160,000

Apply Stefan-Boltzmann Law To Sun and Earth

$$E = \sigma T^4$$

- **Sun**

  $E_s = (5.67 \text{ x } 10^{-8} \text{ W/m}^2 \text{ K}^4) * (6000\text{K})^4$

  $= 73{,}483{,}200 \text{ W/m}^2$

- **Earth**

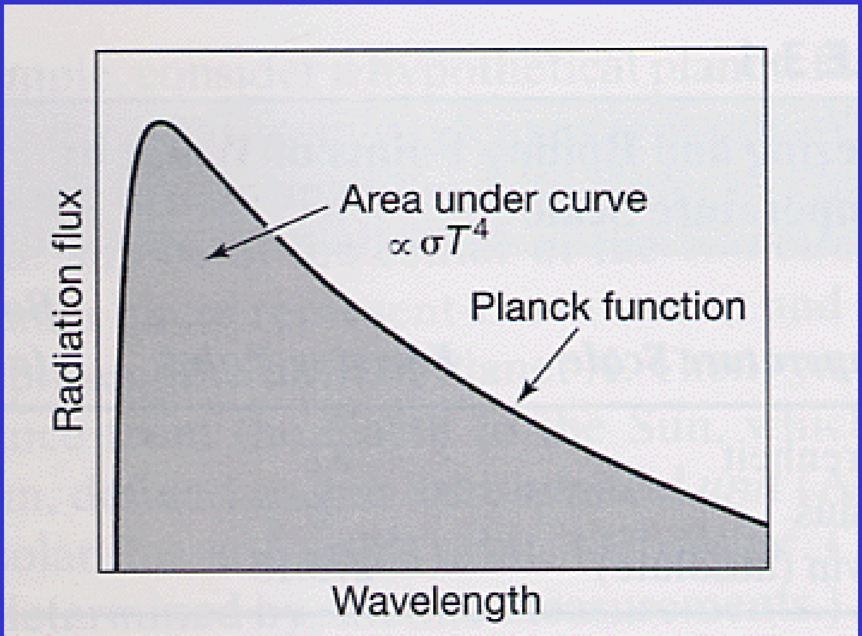
  $E_e = (5.67 \text{ x } 10^{-8} \text{ W/m}^2 \text{ K}^4) * (300\text{K})^4$

  $= 459 \text{ W/m}^2$

- Sun emits about 160,000 times more radiation per unit area than the Earth because Sun’s temperature is about 20 times higher than Earth’s temperature.

  ➔ $20^4 = 160{,}000$

Energy Emitted from Earth



(from *The Earth System*)

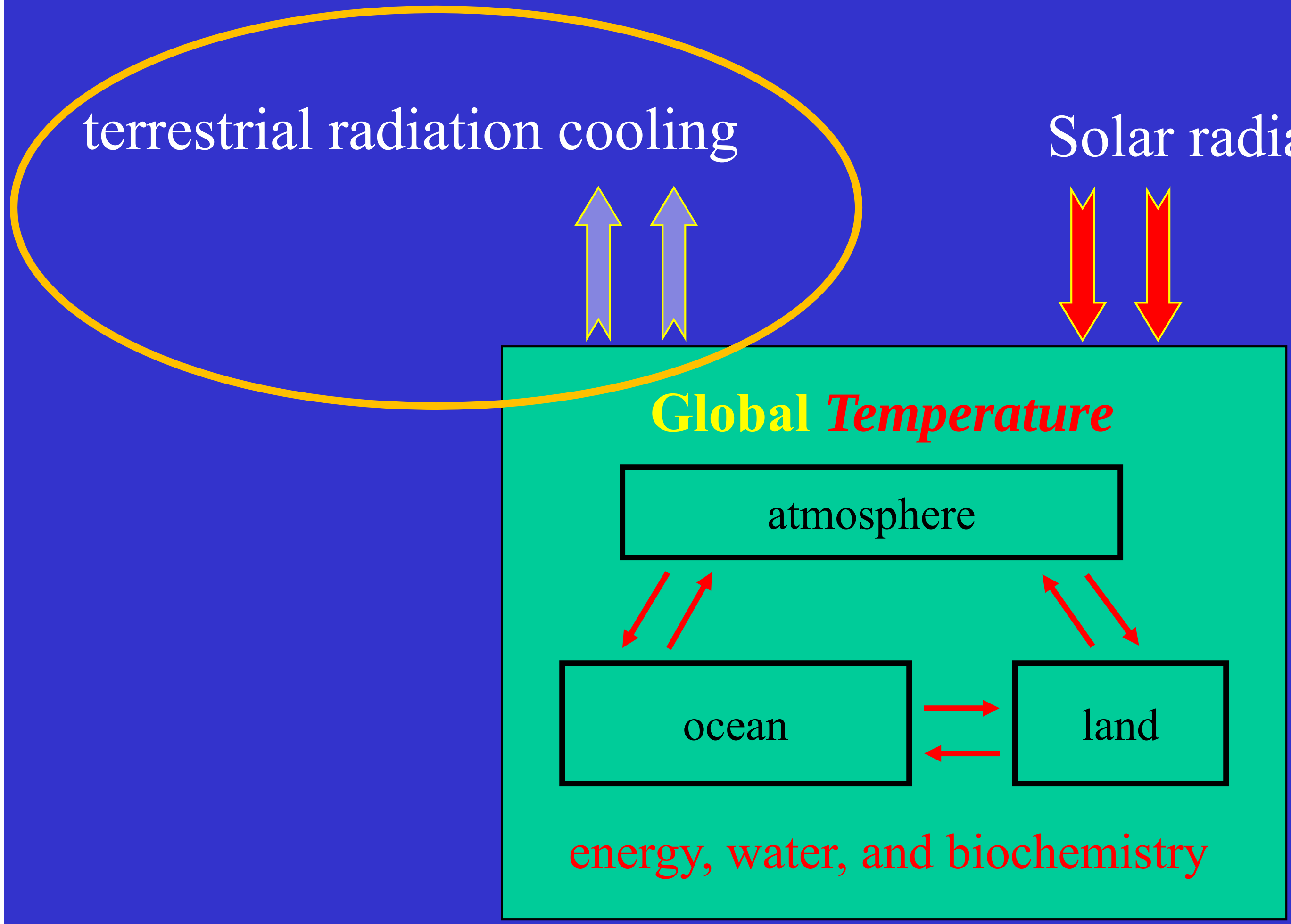
- **The Stefan-Boltzmann Law**

  The energy flux emitted by a blackbody is related to the fourth power of the body's absolute temperature

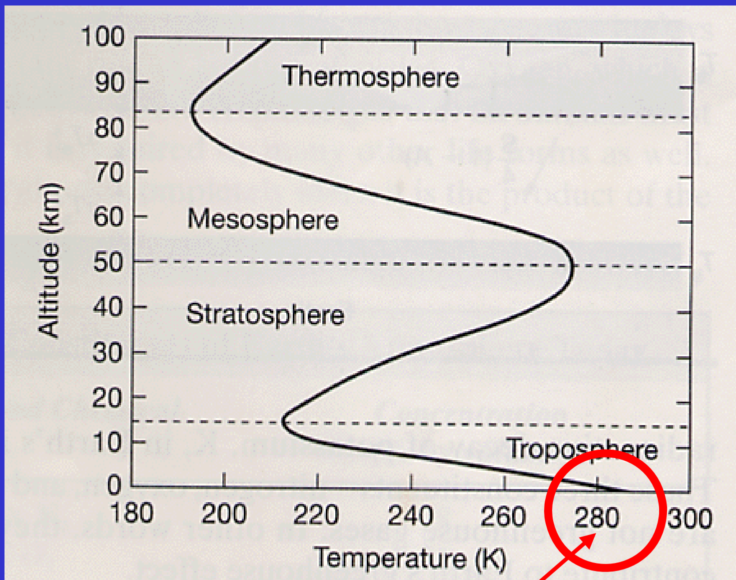
  $\mathbf{F = \sigma T^4}$ where σ is 5.67×10^{-8} W/m^2/K

- **Energy emitted from the Earth**
  = (blackbody emission) x (total area of Earth)
  = (σT_e^4) x $(4\pi R^2_{Earth})$

Global *Energy* Balance



Planetary Energy Balance



(from *Global Physical Climatology*)

- **Energy emitted by Earth = Energy absorbed by Earth**

$$\sigma T_e^4 \ \times \ (4\pi R^2_{Earth}) = S \ \pi R^2_{Earth} \ \times \ (1-A)$$

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

$$= 1370/4 \ W/m^2 * (1-A)$$

$$= 342.5 \ W/m^2 * (1-A)$$

$$= 240 \ W/m^2$$

- **Earth's *blackbody* temperature**

T_e = 255 K (-18C)

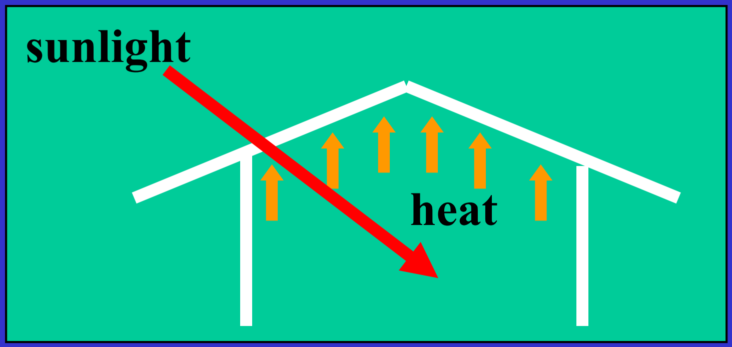
Earth's *surface* temperature

T_S = 288 K (15C)

greenhouse effect (33C) !!

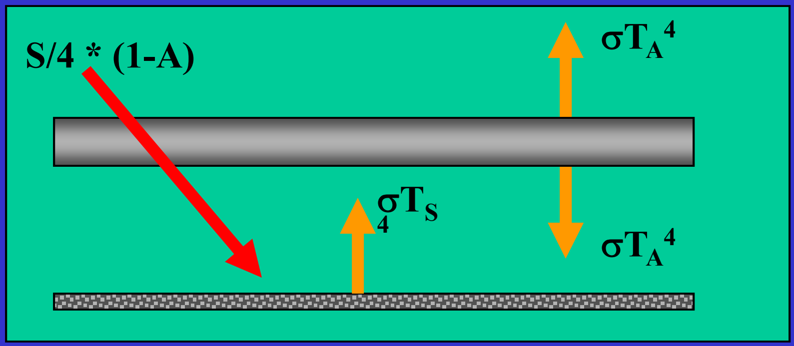
Layer Model

Greenhouse



- allow sunlight to come in
- trap heat inside the house

Atmosphere



- For Earth's surface:

  $S/4*(1\text{-}A) + \sigma T_A^4 = \sigma T_S^4$

- For the atmosphere:

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

➔ $T_A = T_e =$ **255K**

➔ $T_s = 2^{1/4}\, T_A = 303K$

Greenhouse Gases

Important Atmospheric Greenhouse Gases

Name and Chemical Symbol	*Concentration (ppm by volume)*
Water vapor, H_2O	0.1 (South Pole)–40,000 (tropics)
Carbon dioxide, CO_2	360
Methane, CH_4	1.7
Nitrous oxide, N_2O	0.3
Ozone, O_3	0.01 (at the surface)
Freon-11, CCl_3F	0.00026
Freon-12, CCl_2F_2	0.00047

Factors Determine Planet Temperature

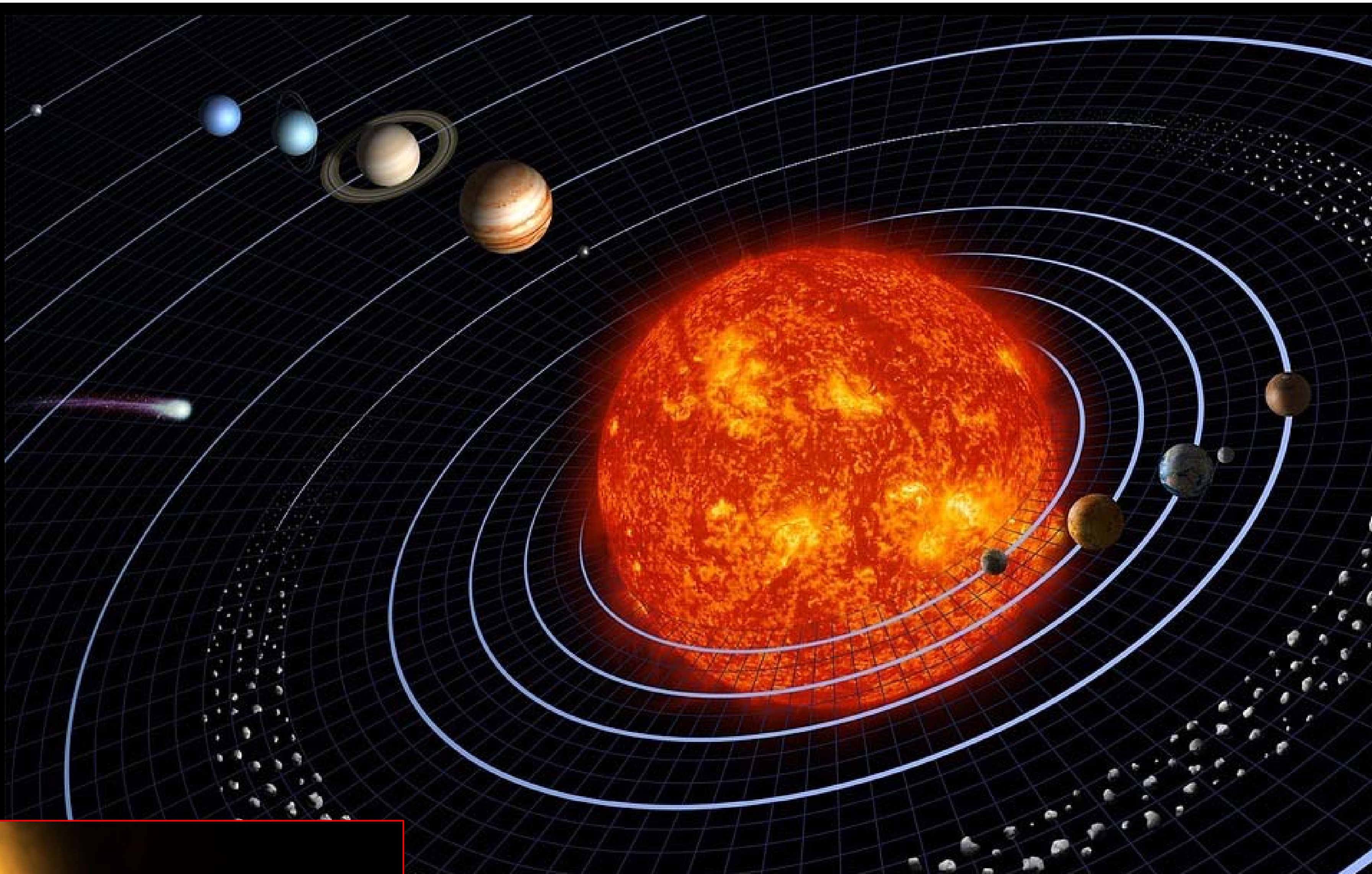
- **Energy emitted by Earth = Energy absorbed by Earth**

$$\sigma T_e^4 \ \mathrm{x} \ (4\pi R^2_{Earth}) = S \pi R^2_{Earth} \ \mathrm{x} \ (1\text{-}A)$$

$$\sigma T_e^4 = S/4 * (1\text{-}A)$$

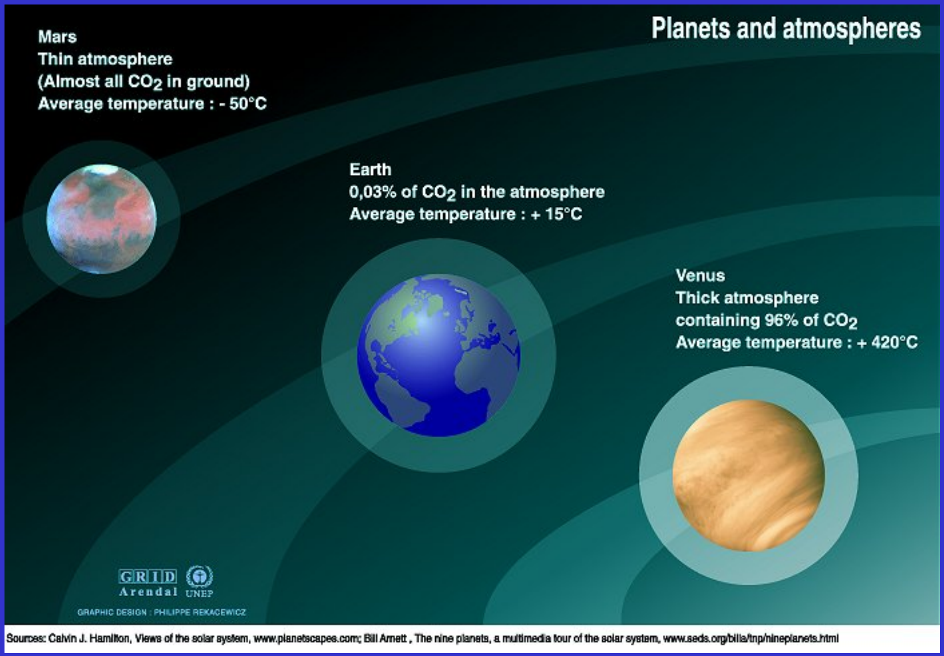
\+ •••••

- ❑ Distance from the Sun
- ❑ Albedo
- ❑ Greenhouse effect



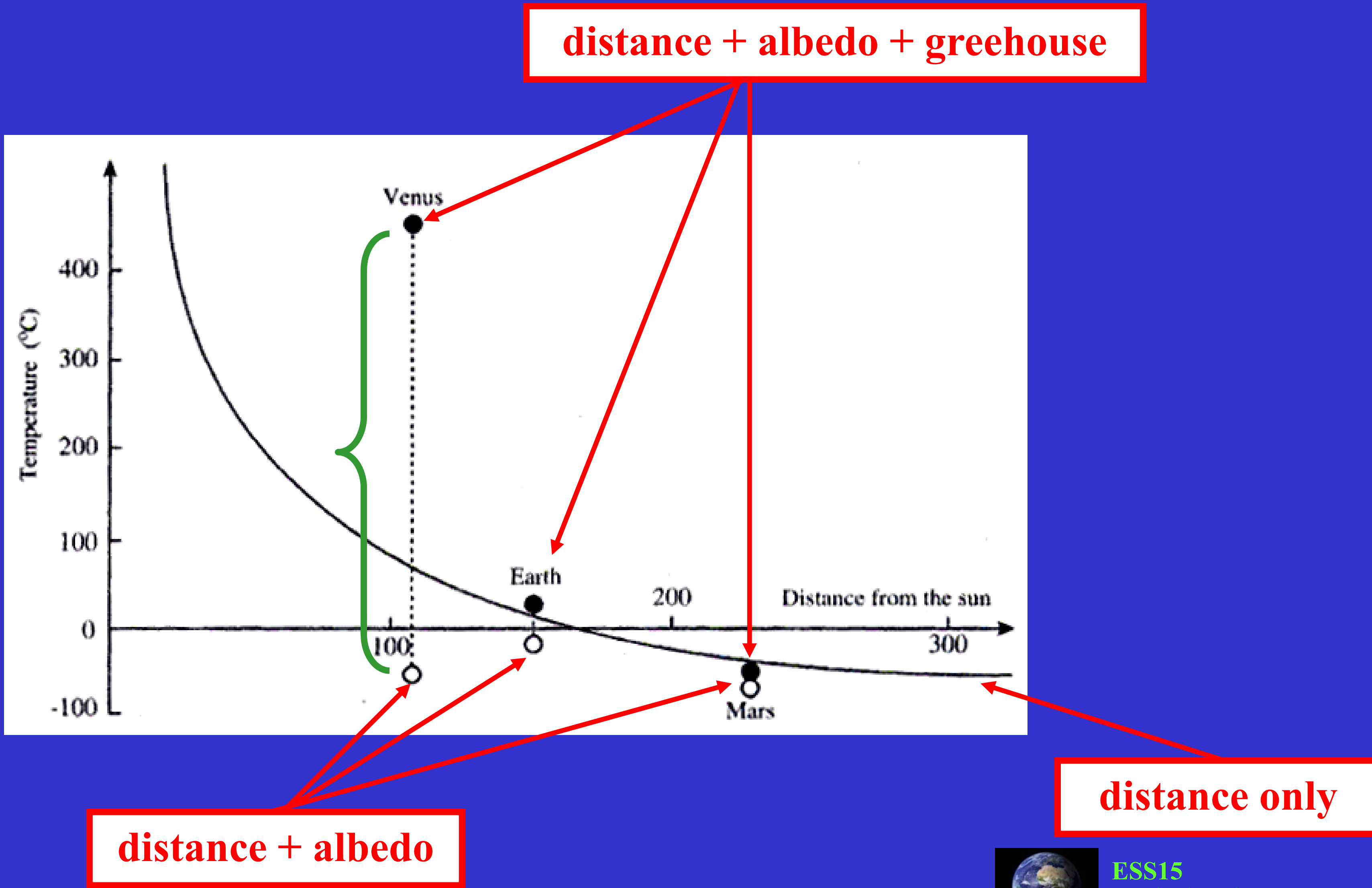

Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune

Mars, Earth, and Venus



Planet	Distance to the Sun	Radius	Planetary Albedo	Mean Surface Temperature
Venus	0.72 AU	6,052 km	0.80	730°K
Earth	1.00 AU	6,370 km	0.30	288°K
Mars	1.52 AU	3,397 km	0.22	218°K

Global Temperature



ESS15
Prof. Jin-Yi Yu

Greenhouse Effects

- On Venus → 510°K (very large!!)
- On Earth → 33°K
- On Mars → 6°K (very small)

Why Large Greenhouse Effect On Venus?

- **Venus is very close to the Sun**

➔ Venus temperature is very high

➔ Very difficult for Venus's atmosphere to get saturated in water vapor

➔ Evaporation keep on bringing water vapor into Venus's atmosphere

➔ Greenhouse effect is very large

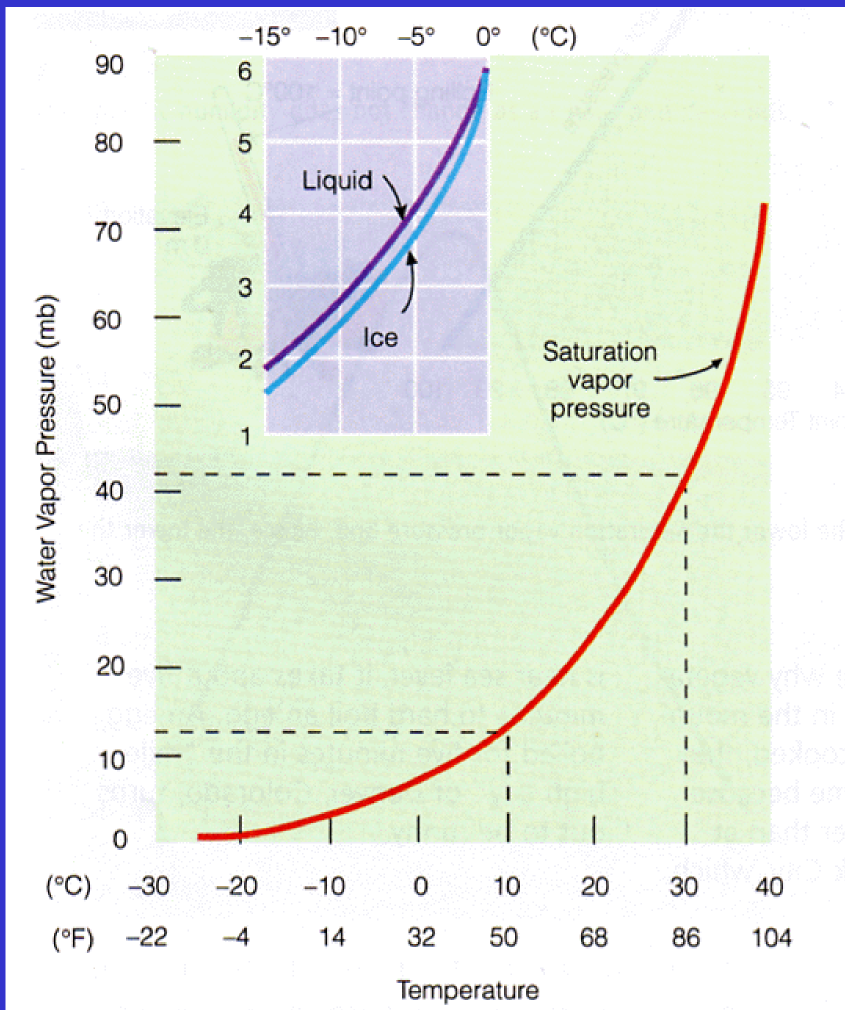
➔ A "run away" greenhouse happened on Venus

➔ Water vapor is dissociated into hydrogen and oxygen

➔ Hydrogen then escaped to space and oxygen reacted with carbon to form carbon dioxide

➔ **No liquid water left on Venus**

Saturation Vapor Pressure



- Saturation vapor pressure describes how much water vapor is needed to make the air saturated at any given temperature.
- Saturation vapor pressure depends primarily on the air temperature in the following way:

$$\frac{de_s}{dT} = \frac{L}{T(\alpha_v - \alpha_l)}$$

The Clausius-Clapeyron Equation

➔ $$e_s \cong 6.11 \bullet \exp\left\{\frac{L}{R_v}\left(\frac{1}{273} - \frac{1}{T}\right)\right\}$$

- Saturation pressure increases exponentially with air temperature.

L: latent heat of evaporation; α: specific volume of vapor and liquid

Why Small Greenhouse Effect on Mars?

- **Mars is too small in size**

→ Mars had no large internal heat

→ Mars lost all the internal heat quickly

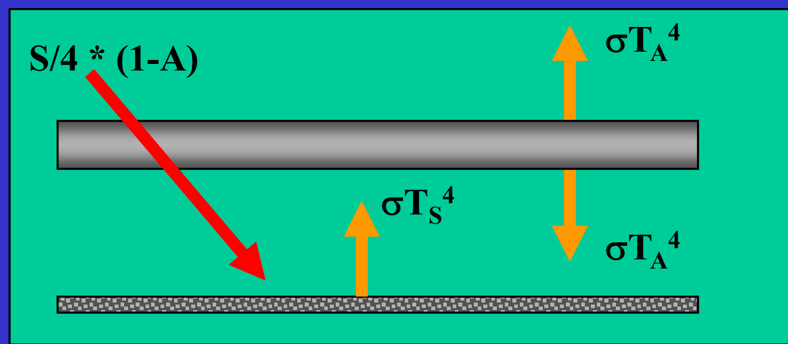
→ No tectonic activity on Mars

→ Carbon can not be injected back to the atmosphere

→ Little greenhouse effect

→ **A very cold Mars!!**

Atmosphere



- How big is the greenhouse effect in the figure above?

  (a) **S/4 * (1-A)**

  (b) σT_s^4

  (c) σT_A^4