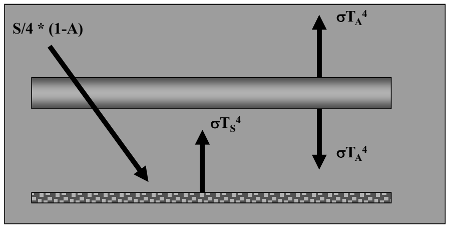
Lecture 4: Global Energy Balance



- ❑ Blackbody Radiation
- ❑ Layer Model
- ❑ Greenhouse Effect

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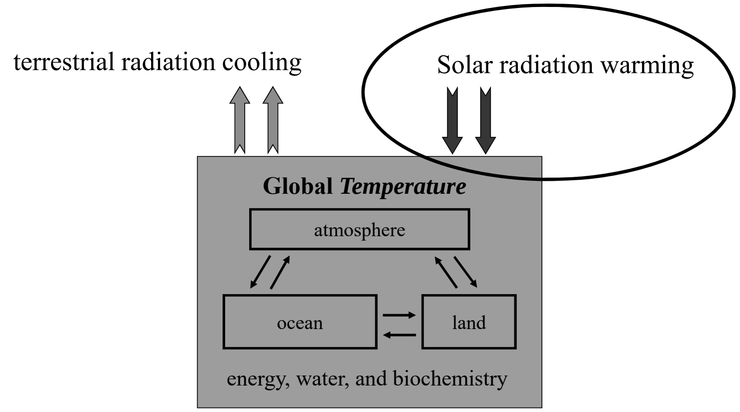
Global *Energy* Balance



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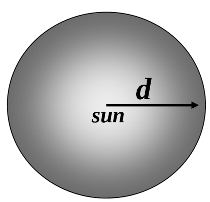
Solar Flux and Flux Density

- ❑ Solar Luminosity (***L***)
  the constant flux of energy put out by the sun

  $L = 3.9 \times 10^{26}$ 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***

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



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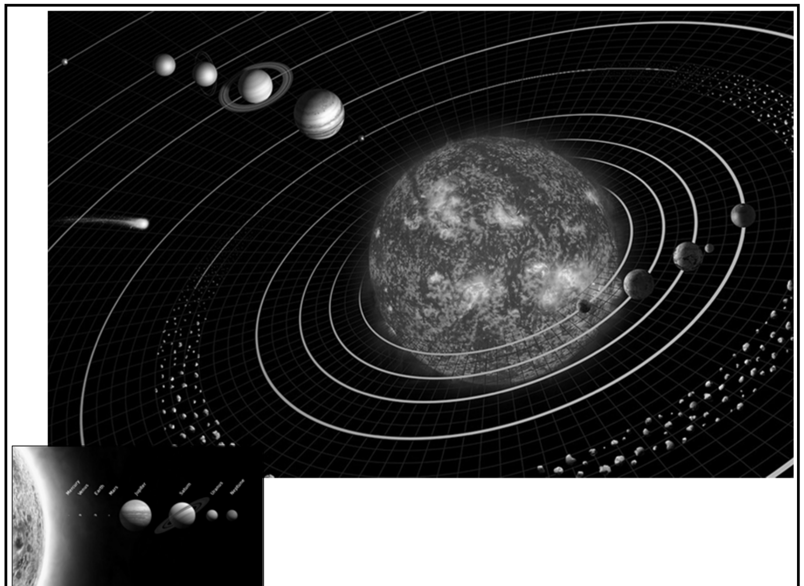


Solar Flux Density Reaching Earth

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

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

$$\boldsymbol{S = L / (4 \pi d^2)}$$
$$\boldsymbol{= (3.9 \times 10^{26}\ W) / [4 \times 3.14 \times (1.5 \times 10^{11}\ m)^2]}$$
$$\boldsymbol{= 1370\ W/m^2}$$

Solar Energy Incident On the Earth

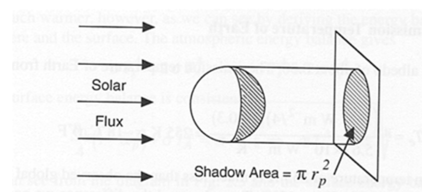
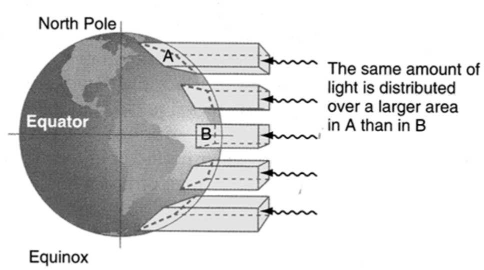


Fig. 2.2 Diagram showing the shadow area of a spherical planet.

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

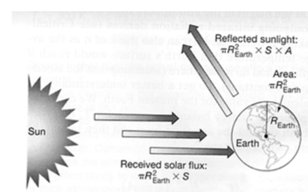
Zenith Angle and Insolation



(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



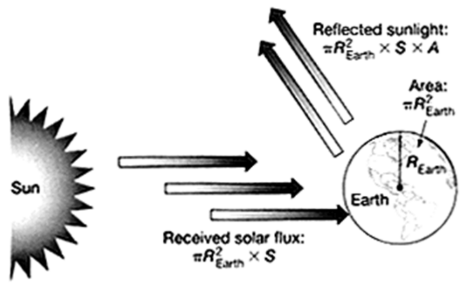
BOX FIGURE 3-1
The amount of sunlight received by and reflected by Earth.

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

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

Albedo = [Reflected] / [Incoming] Sunlight

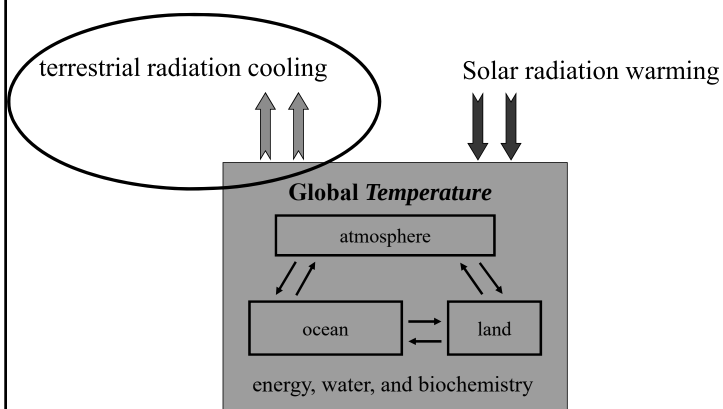


Albedo is the percentage of the sunlight that is reflected back to the space by the planet.

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 x 10^{-8} W/m^2 K^4) * $(6000K)^4$

  = 73,483,200 W/m^2

- ❑ **Earth**

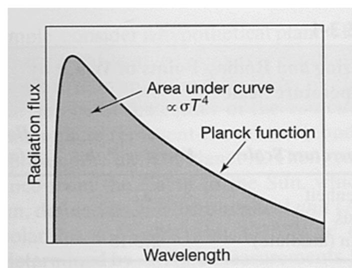
  E_e = (5.67 x 10^{-8} W/m^2 K^4) * $(300K)^4$

  = 459 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

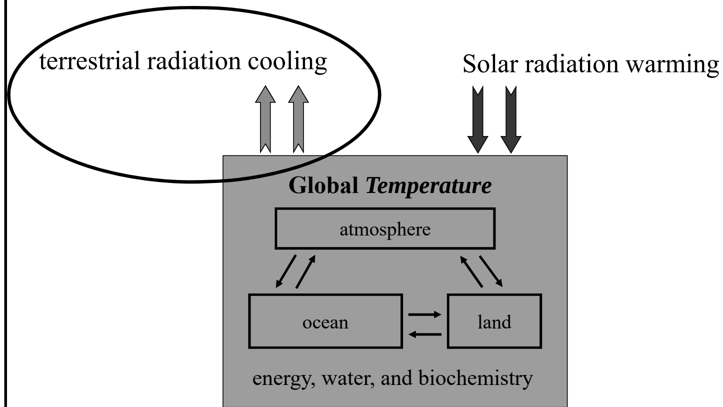
  F = σT⁴ where σ is 5.67x10^{-8} $W/m^2/K$

- **Energy emitted from the Earth**

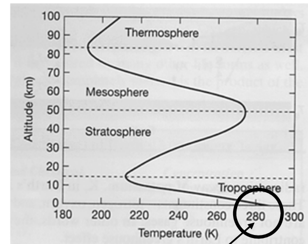
  = (blackbody emission) x (total area of Earth)

  = (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 *surface* temperature

T_S = 288 K (15C)

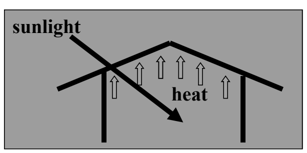
- **Earth's *blackbody* temperature**

T_e = 255 K (-18C)

greenhouse effect (33C) !!

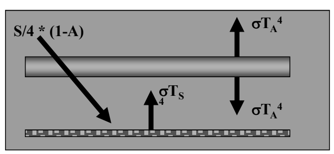
Layer Model

Greenhouse



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

Atmosphere



- For Earth's surface:

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

- 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**

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

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

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

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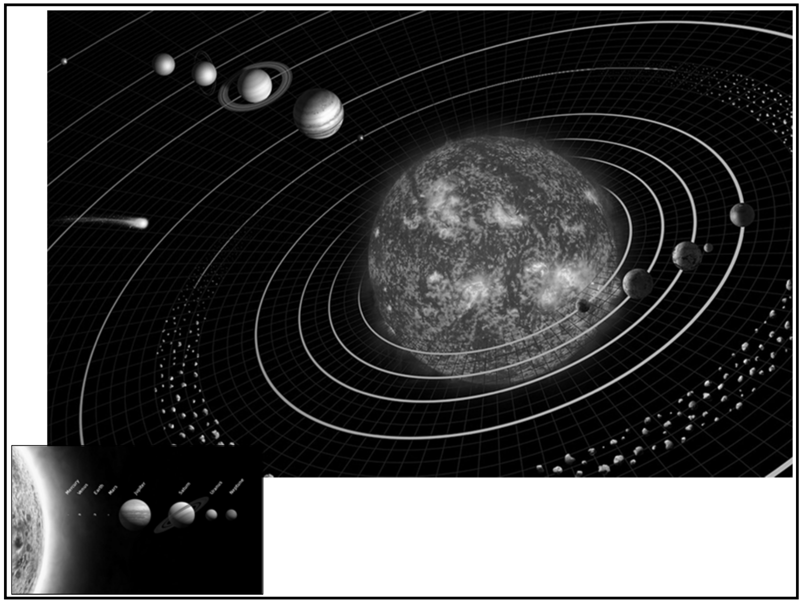
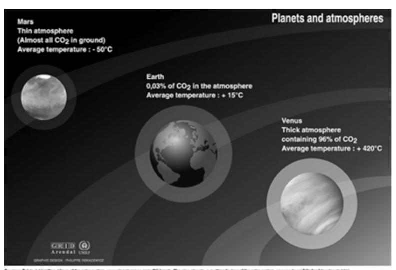


Mars, Earth, and Venus



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

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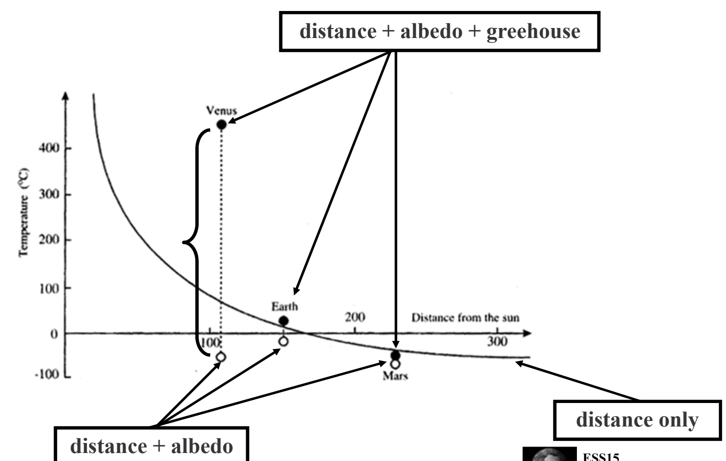
Global Temperature



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Greenhouse Effects

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

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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**

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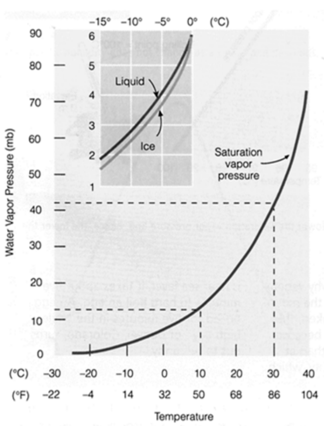
Saturation Vapor Pressure



❑ 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

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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!!**

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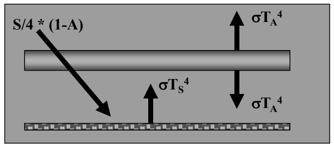
Atmosphere



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

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

  (b) $\boldsymbol{\sigma T_s^4}$

  (c) $\boldsymbol{\sigma T_A^4}$

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