Lecture 3: Global Energy Cycle

- Planetary energy balance
- Greenhouse Effect
- Vertical energy balance
- Latitudinal energy balance
- Seasonal and diurnal cycles

Solar Flux and Flux Density

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

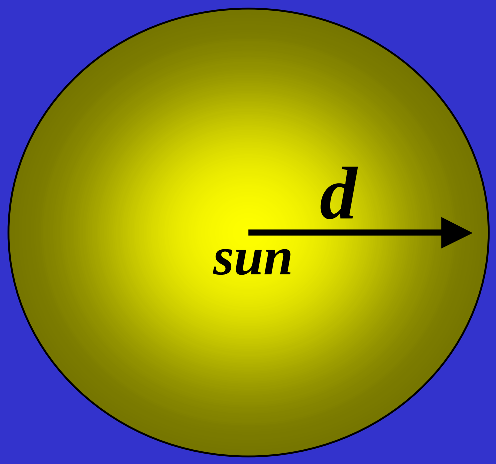
  the constant flux of energy put out by the sun

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

- Solar Flux Density (***S_d***)

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

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



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

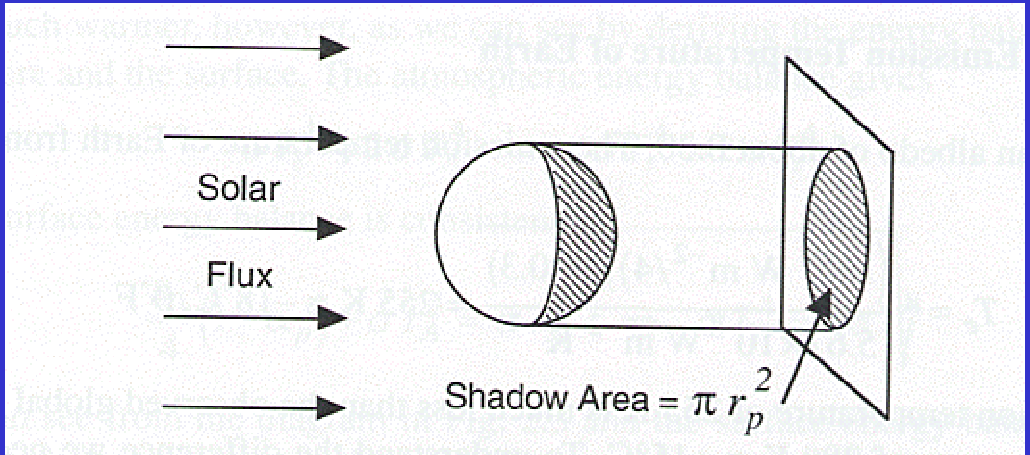
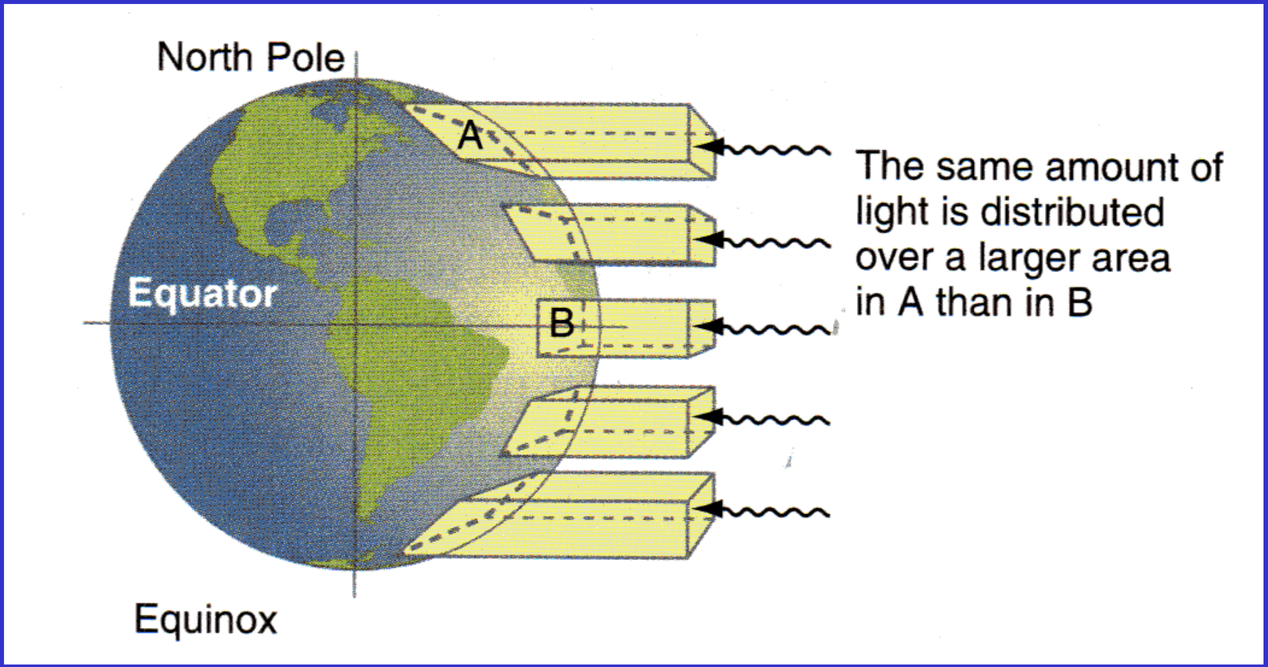


Fig. 2.2 Diagram showing the shadow area of a spherical planet.

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

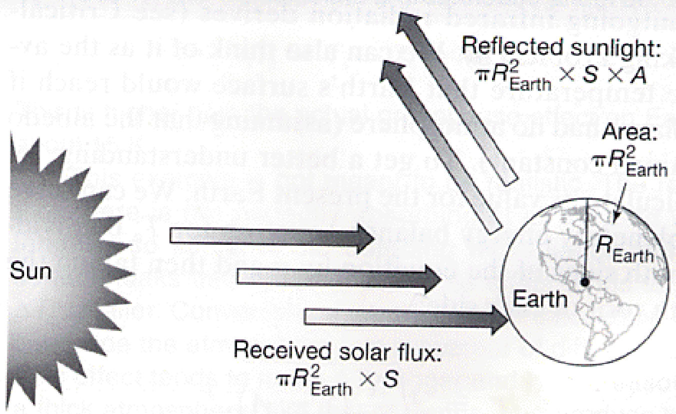
Zenith Angle and Insolation



(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*)

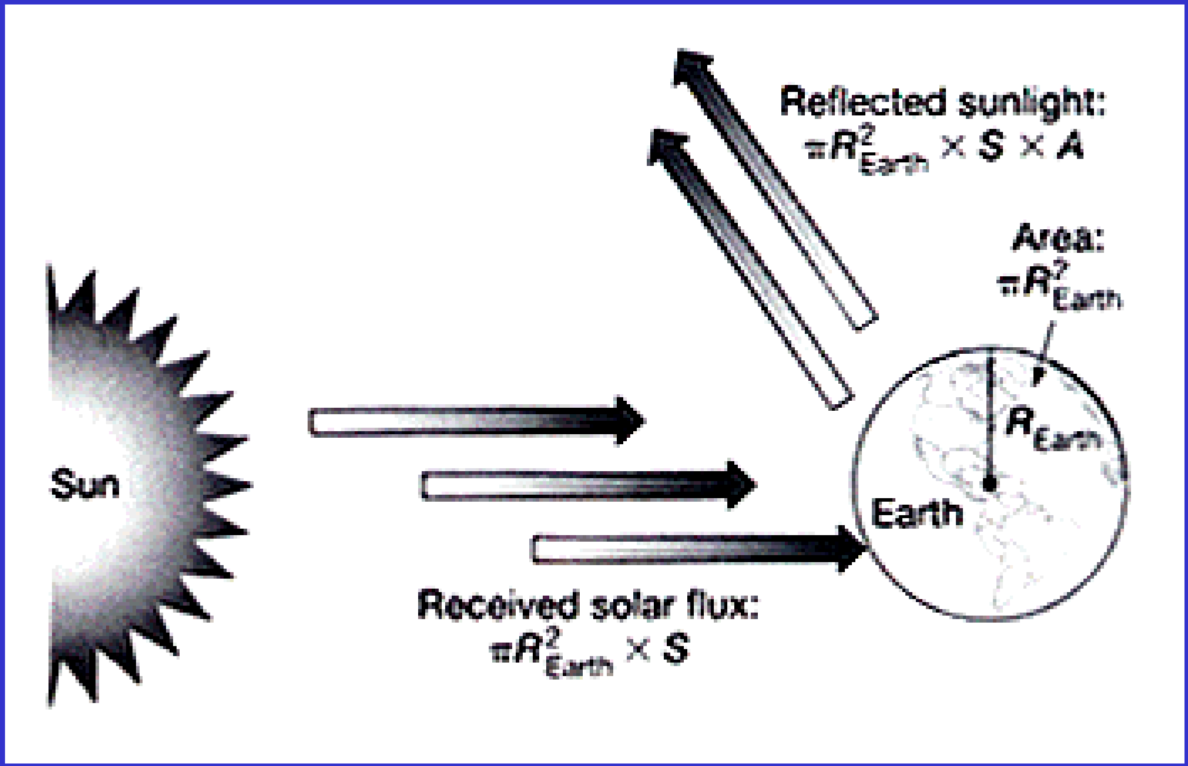
- **Solar Constant (S)**
  = solar flux density reaching the Earth
  = 1370 W/m^2

- **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.

Blackbody Radiation

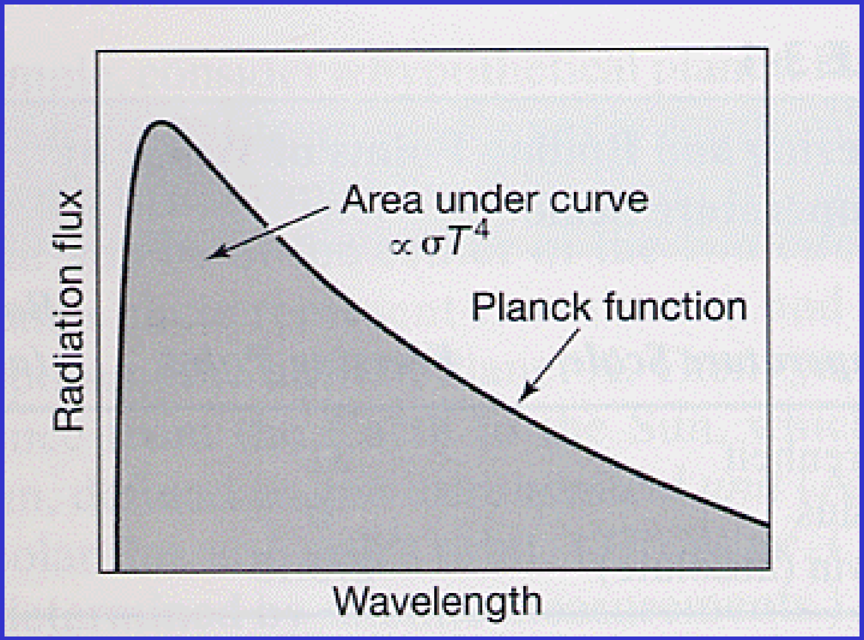
- Blackbody

  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.

Energy Emitted from Earth



(from *The Earth System*)

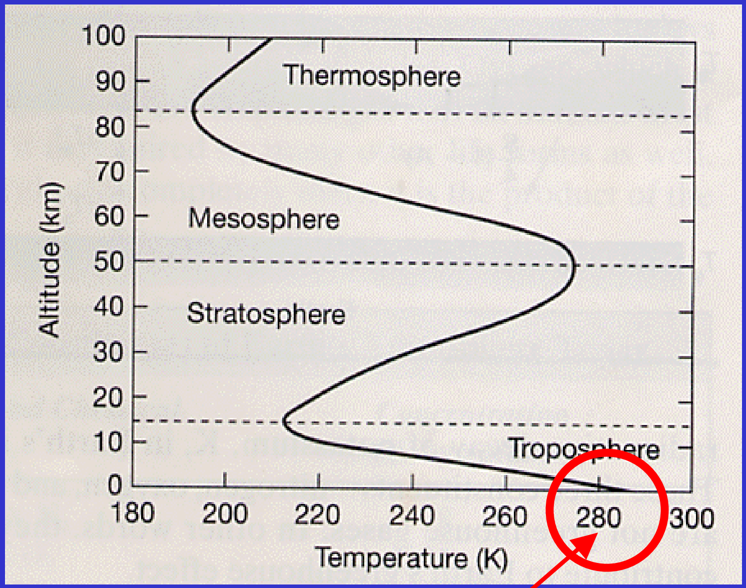
- **The Stefan-Boltzmann Law**

  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 $(4\pi R^2_{Earth})$

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)

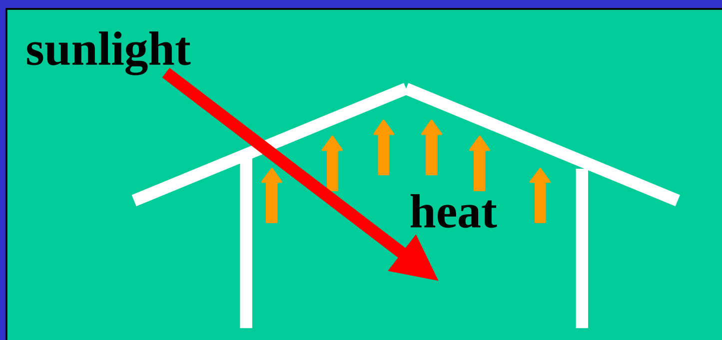
Earth's *surface* temperature

T_S = 288 K (15C)

greenhouse effect (33C) !!

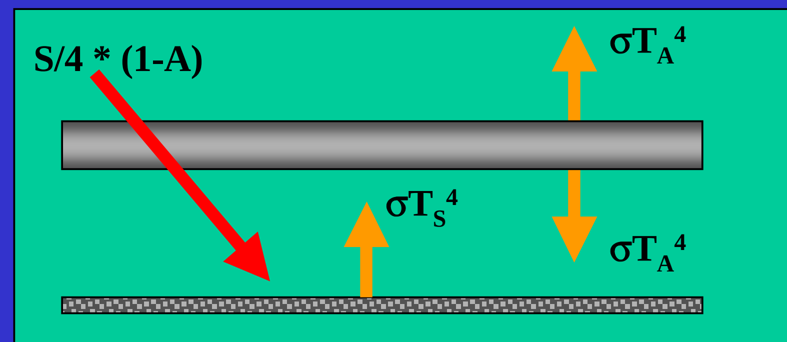
Greenhouse Effect

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**

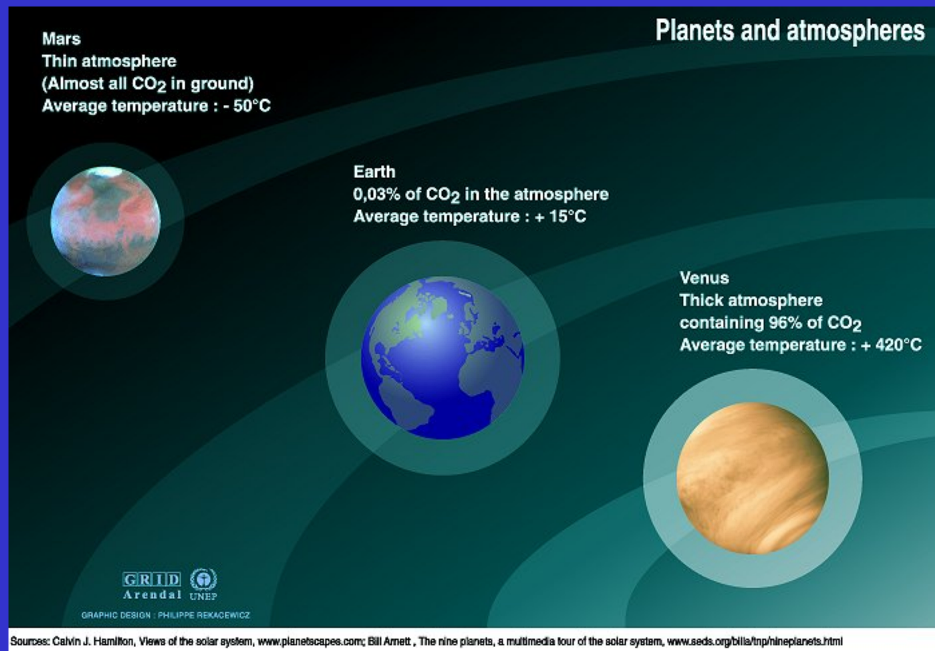
➔ **$T_s = 2^{1/4}\, T_A = $ 303K**

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

Earth, Mars, and Venus

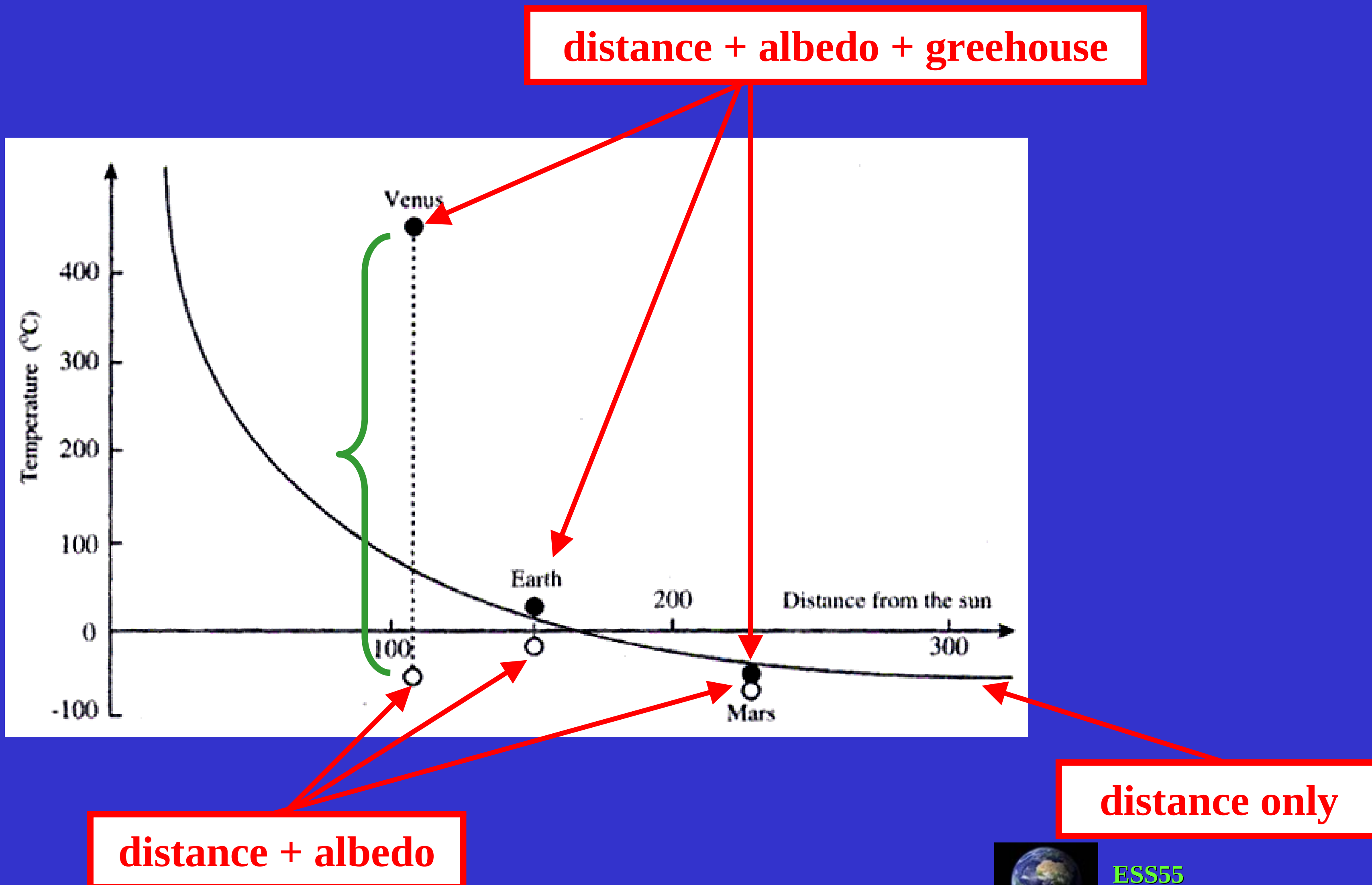


Planet	Distance to the Sun	Radius	Planetary Albedo	Mean Surface Temperature
Venus	0.72 AU	12,104 km	0.80	730°K
Earth	1.00 AU	6,370 km	0.30	288°K
Mars	1.52 AU	6,794 km	0.22	218°K

Factors Determine Planet Temperature

- Distance from the Sun
- Albedo
- Greenhouse effect

Global Temperature



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**

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

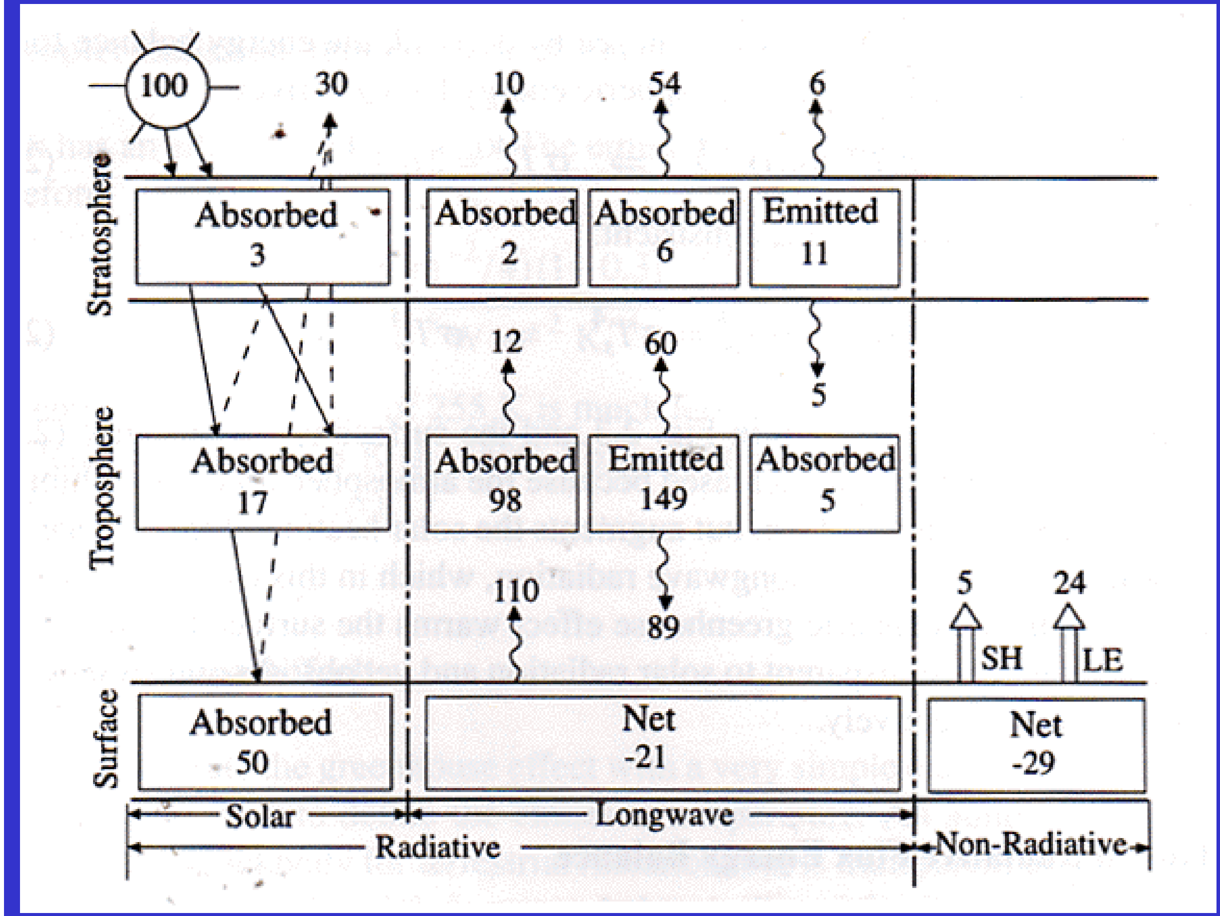
→ No tectonic activity on Mars

→ Carbon can not be injected back to the atmosphere

→ Little greenhouse effect

→ **A very cold Mars!!**

Vertical Distribution of Energy

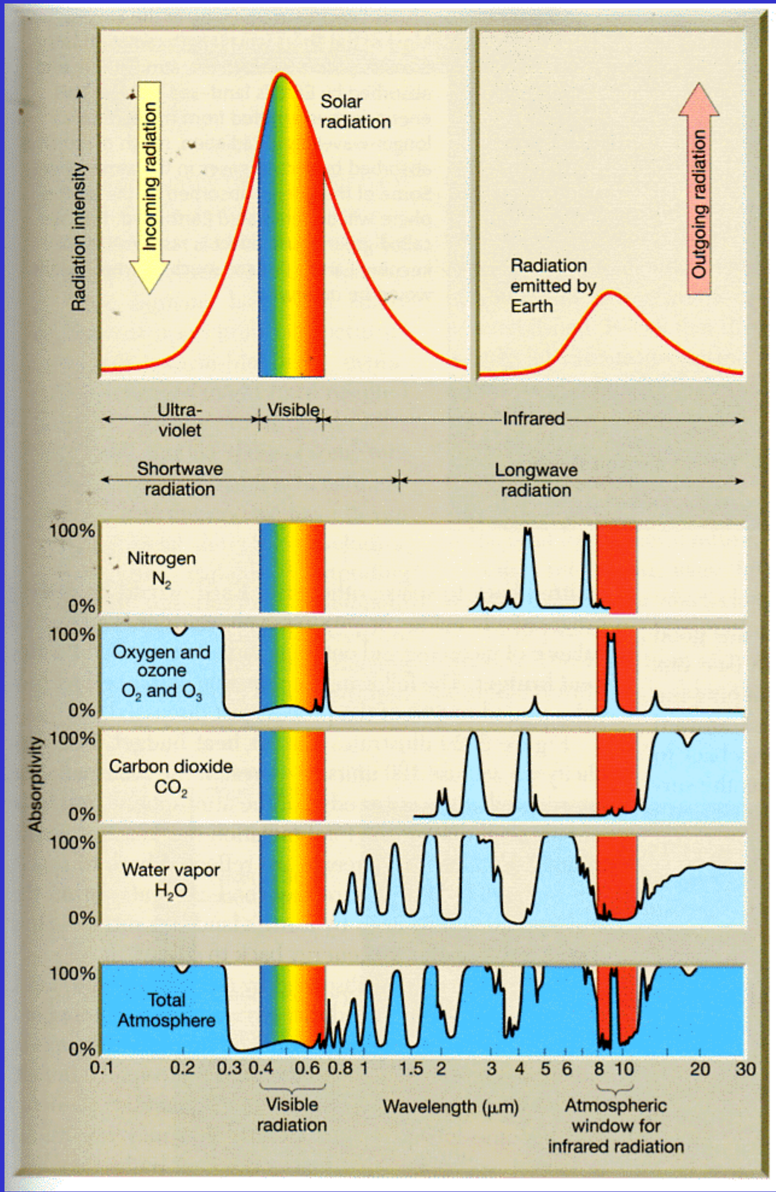


(from *Global Physical Climatology*)

Incoming solar energy (100)

- 70% absorbed
  - 50% by Earth's surface
  - 20% by atmosphere
    - 3% in stratosphere (by ozone and O_2)
    - 17% in troposphere (water vapor & cloud)
- 30% reflected/scattered back
  - 20% by clouds
  - 6% by the atmosphere
  - 4% by surface

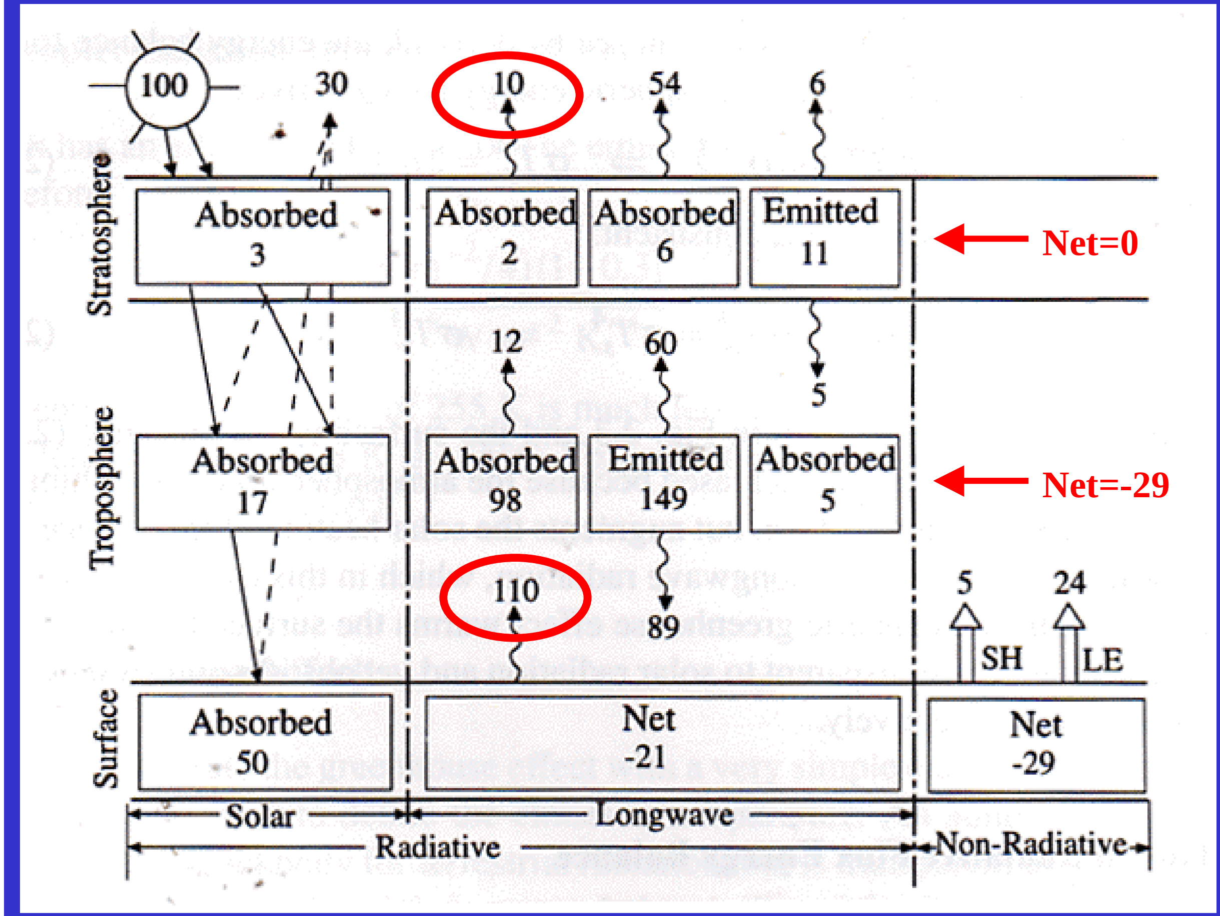
Selective Absorption and Emission



- ❑ The atmosphere is not a perfect blackbody, it absorbs some wavelength of radiation and is transparent to others (such as solar radiation). ➔ Greenhouse effect.
- ❑ Objective that selectively absorbs radiation usually selectively emit radiation at the same wavelength.
- ❑ For example, water vapor and CO2 are strong absorbers of infrared radiation and poor absorbers of visible solar radiation.

(from *The Atmosphere*)

Vertical Distribution of Energy



(from *Global Physical Climatology*)

Outgoing radiation (70 units)

- 10 units by the surface
- 60 units by the atmosphere

  54 units by troposphere

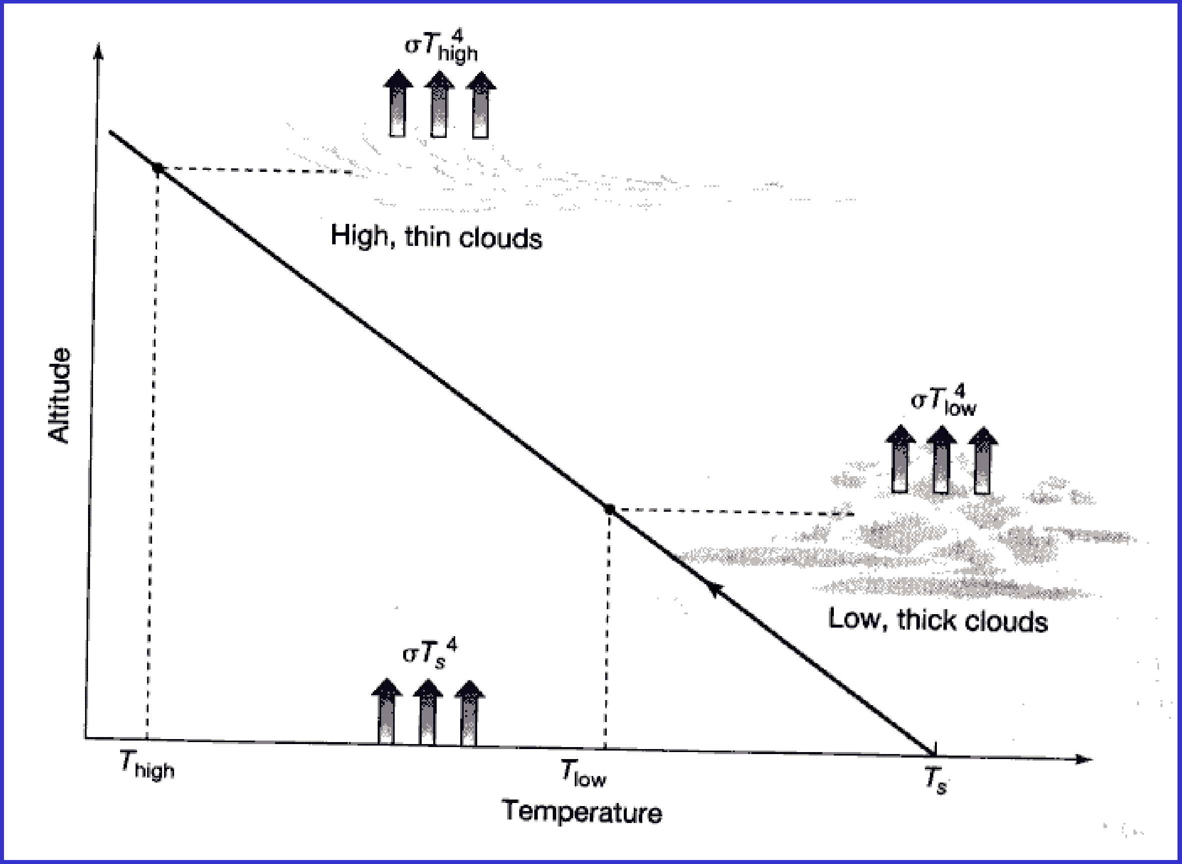
  6 units by stratosphere
- Greenhouse effect (89 units) from the atmosphere back to the surface
- Water vapor and cloud provide 80% of the greenhouse effect

Greenhouse Effect and Diurnal Cycle

- The very strong downward emission of terrestrial radiation from the atmosphere is crucial to main the relatively small diurnal variation of surface temperature.
- If this large downward radiation is not larger than solar heating of the surface, the surface temperature would warm rapidly during the day and cool rapidly at the night.

  ➔ a large diurnal variation of surface temperature.
- The greenhouse effect not only keeps Earth’s surface warm but also limit the amplitude of the diurnal temperature variation at the surface.

Important Roles of Clouds In Global Climate



(from The Earth System)

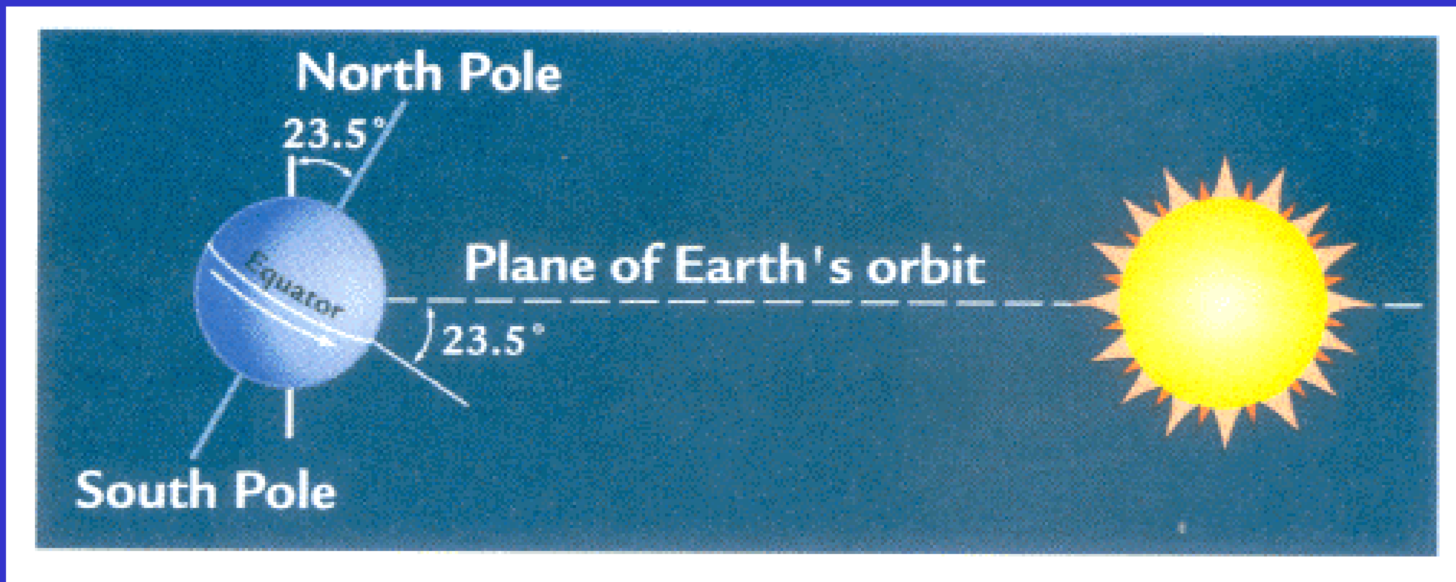
Latitudinal and Seasonal Variations

- The amount of energy absorbed and emitted by Earth geographically and seasonally.

- **Seasonal variations:** the angle of inclination is responsible for the seasonal variation in the amount of solar energy distributed at the top of the atmosphere.

- **Latitudinal variations:** the variations of solar energy in latitude is caused by changes in:
  (a) the angle the sun hits Earth's surface = solar zenith angle
  (b) albedo
  (c) the number of day light hours

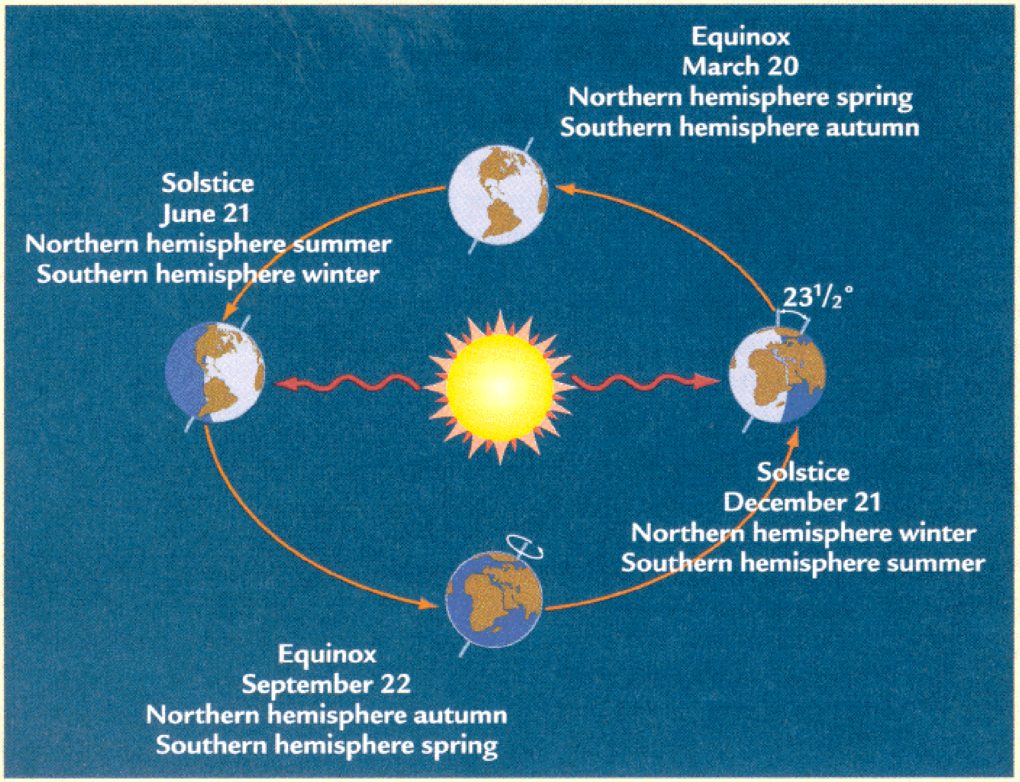
Angle of Inclination = the Tilt



(from *Earth's Climate: Past and Future*)

- At present-day, the axis is tilted at an angle of 23.5°, referred to as Earth's "obliquity", or "tilt".
- The Sun moves back and forth through the year between 23.5°N and 23.5°S.
- Earth's 23.5° tilt also defines the 66.5° latitude of the Artic and Antarctic circles. No sunlight reaches latitudes higher than this in winter day.
- The tilt produces ***seasons***!!

Seasons and the Elliptical Orbit



Orbital changes All aspects of Earth's present-day orbit have changed with time: the tilt of its axis, the shape of its path around the Sun, and the positions of the seasons on this path. These changes in orbit have driven climatic changes on Earth. (Adapted from F. K. Lutgens and E. J. Tarbuck, *The Atmosphere* [Englewood Cliffs, N.J.: Prentice-Hall, 1992].)

(from *Earth's Climate: Past and Future*)

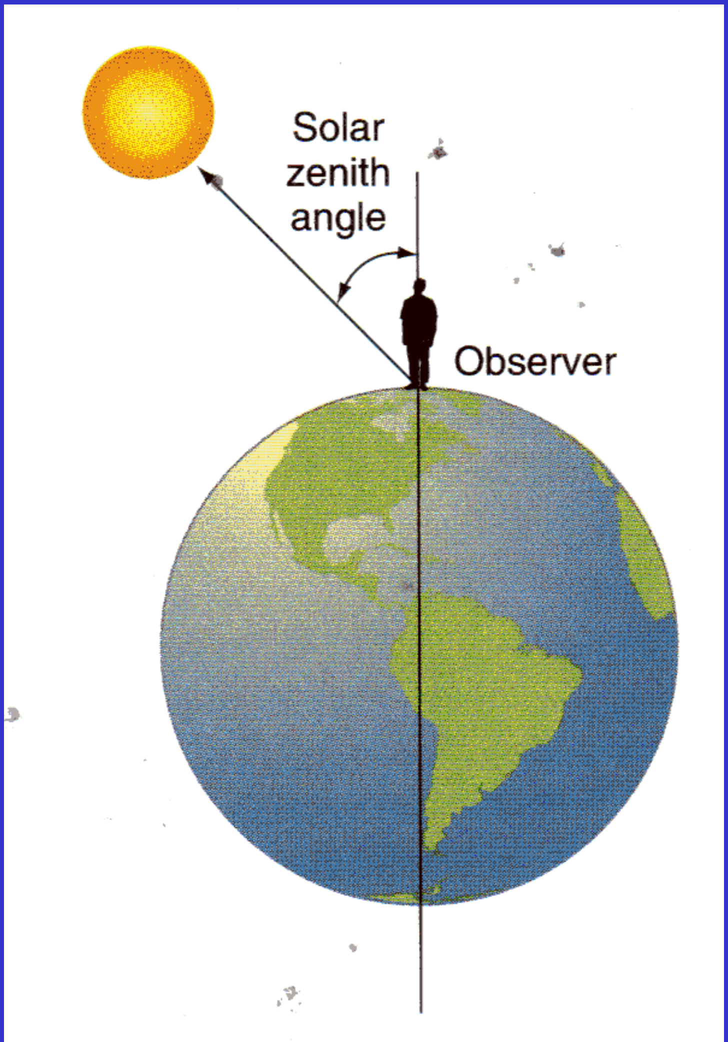
- Seasons

  Solstices: mark the longest and shortest days of the years (June 21 and December 21 in the northern hemisphere, the reverse in the southern)

  Equinoxes: the length of night and day become equal in each hemisphere.

- At the present-day orbit, the winter and summer solstices differ from the aphelion and perihelion by about 13 days.

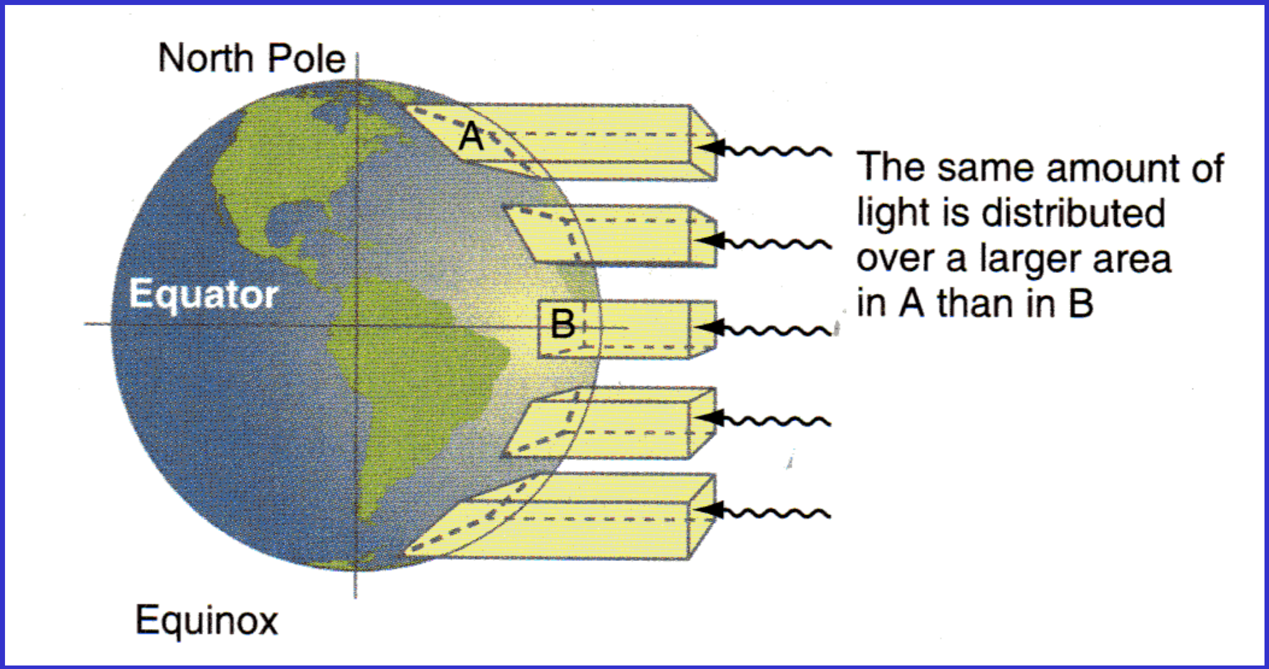
Solar Zenith Angle



- Solar zenith angle is the angle at which the sunlight strikes a particular location on Earth.
- This angle is 0° when the sun is directly overhead and increase as sun sets and reaches 90 ° when the sun is on the horizon.

(from *Meteorology: Understanding the Atmosphere*)

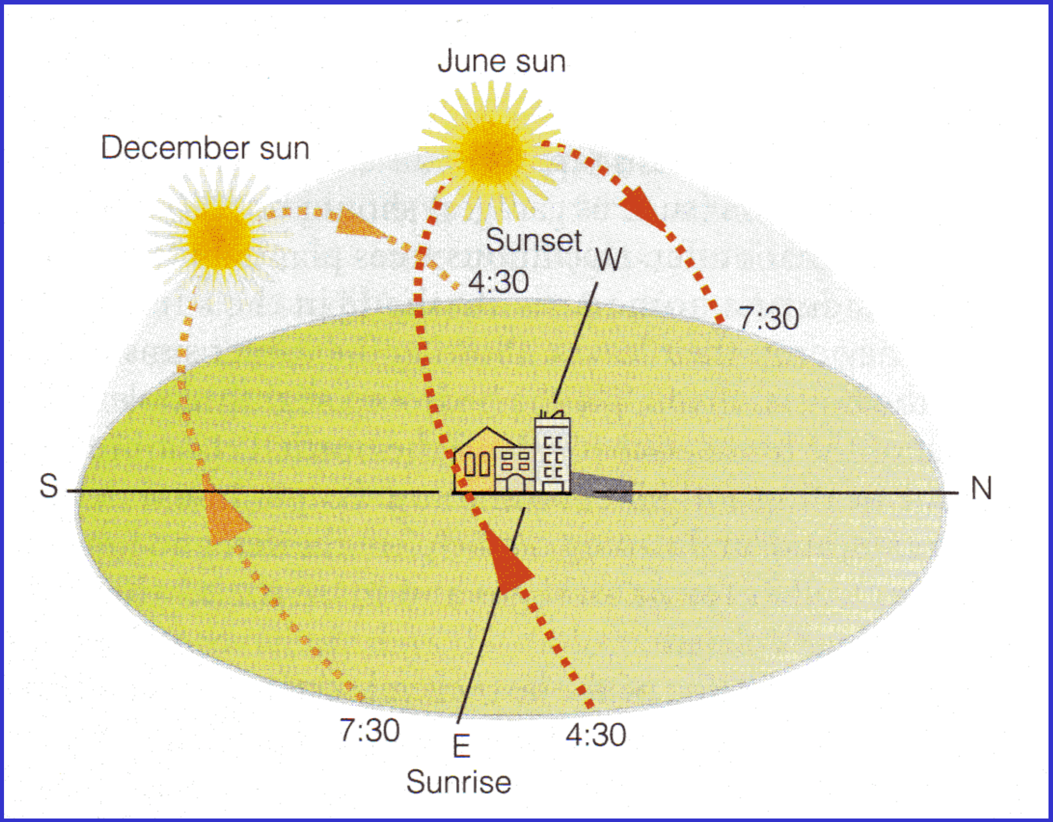
Zenith Angle and Insolation



(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.

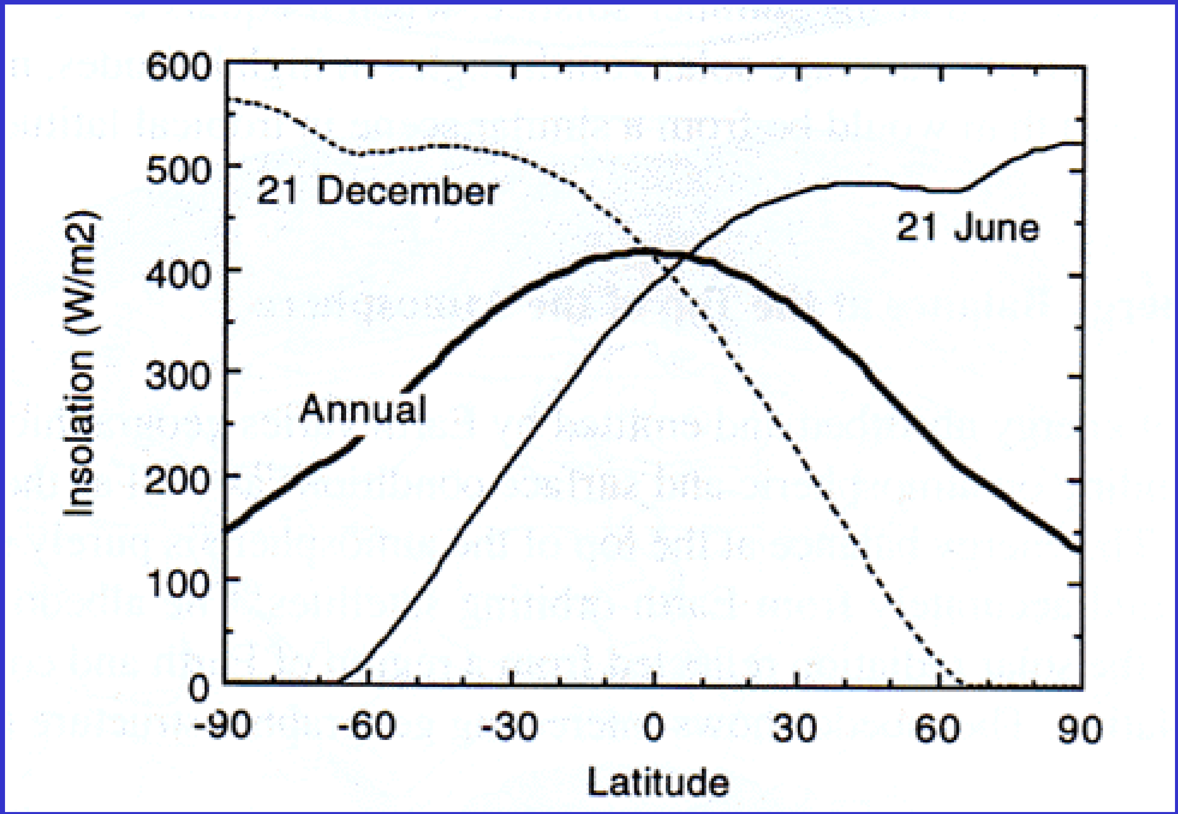
What Determine Zenith Angle?



(from *Meteorology Today)*

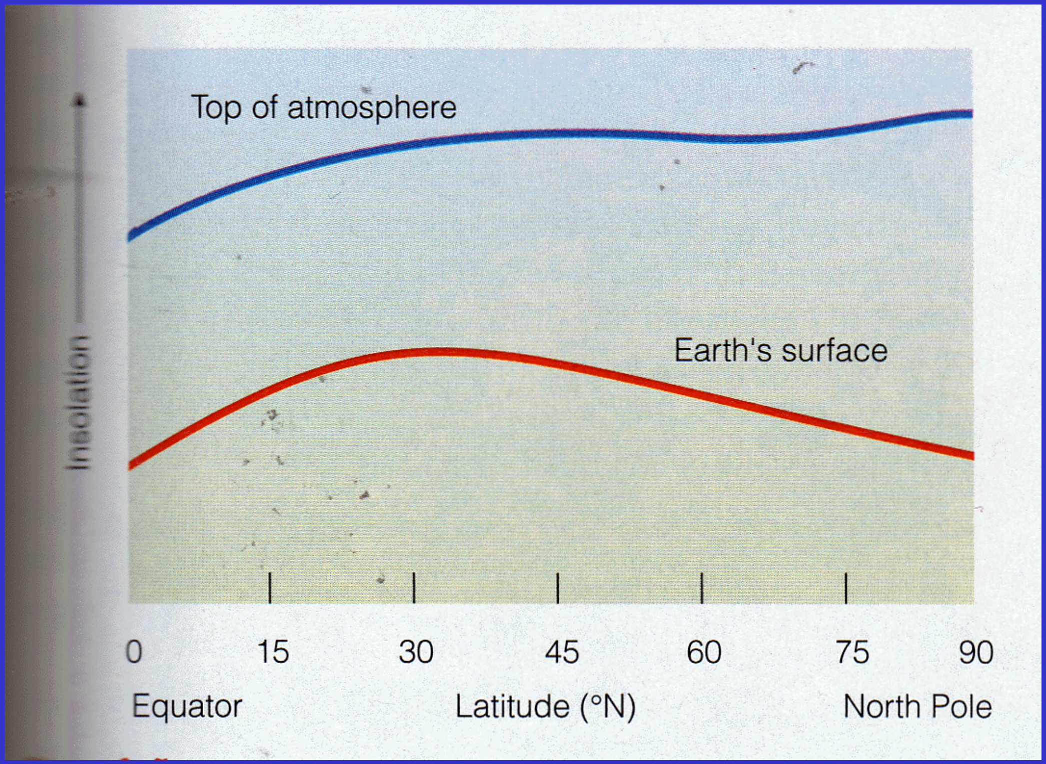
- The solar zenith angle is a function of time of day, time of year, and latitude.

Insolation at Top of Atmosphere



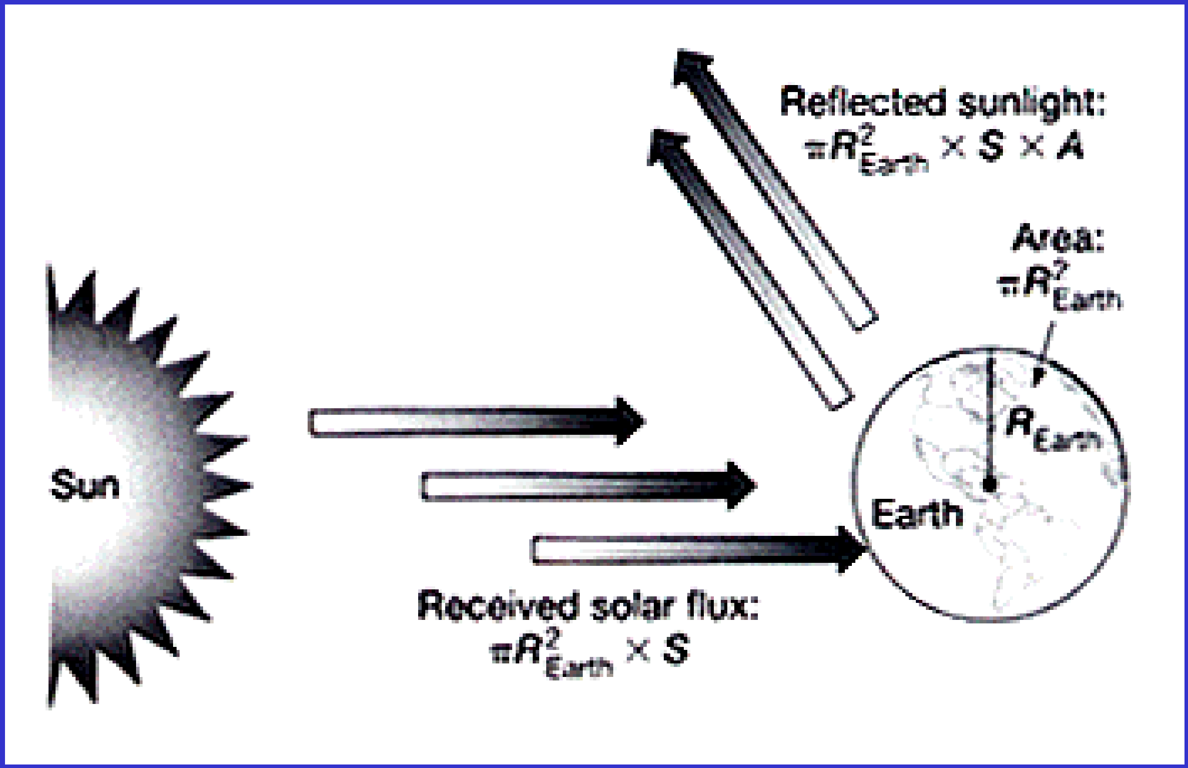
(from *Global Physical Climatology*)

Insolation in Summer Solstice



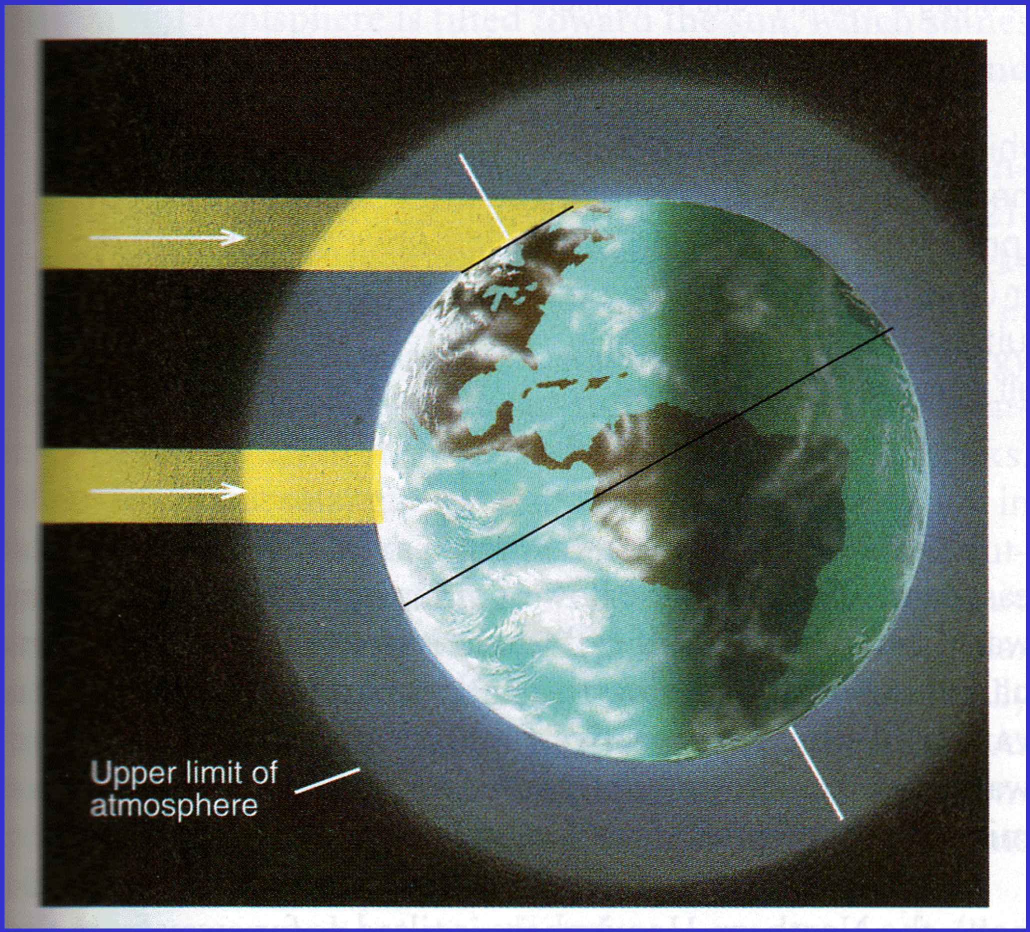
(from *Meteorology Today*)

Albedo = [Reflected] / [Incoming] Sunlight



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

Solar Zenith Angle Affects Albedo



(from *Meteorology Today*)

- The larger the solar zenith angle, the larger the albedo.
- When the zenith angle is large, sunlight has to pass through a thicker layer of the atmosphere before it reaches the surface.
- The thinker the atmospheric layer, more sunlight can be reflected or scattered back to the space.

Surface Types Affect Albedo

TABLE 2-1 Average Albedo Range of Earth's Surfaces

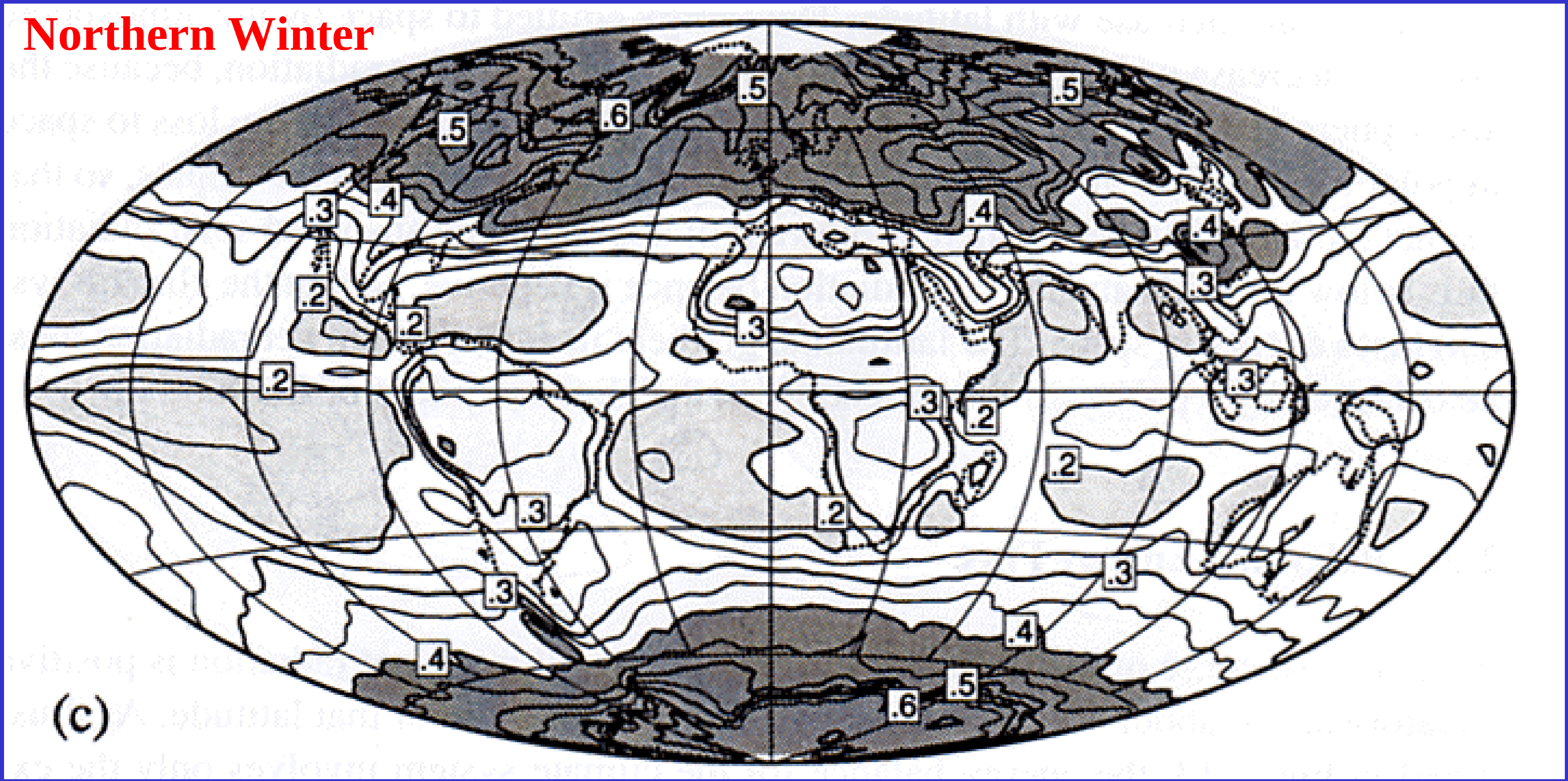
Surface	Albedo range (percent)
Fresh snow or ice	60–90%
Old, melting snow	40–70
Clouds	40–90
Desert sand	30–50
Soil	5–30
Tundra	15–35
Grasslands	18–25
Forest	5–20
Water	5–10

Adapted from W. D. Sellers, Physical Climatology *(Chicago: University of Chicago Press, 1965), and from R. G. Barry and R. J. Chorley,* Atmosphere, Weather, and Climate, *4th ed. (New York: Methuen, 1982).*

(from *Earth's Climate: Past and Future*)

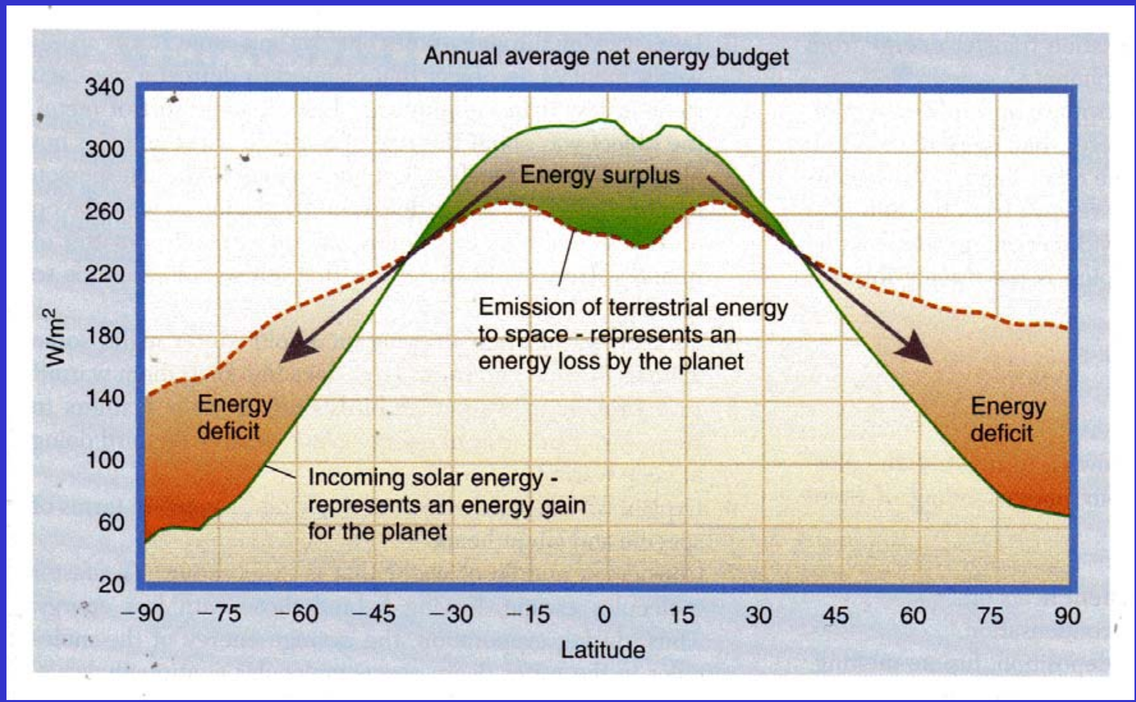
The brighter a color, the more it reflects sunlight.

Global Distribution of Albedo



(from *Global Physical Climatology*)

Latitudinal Variations of Net Energy

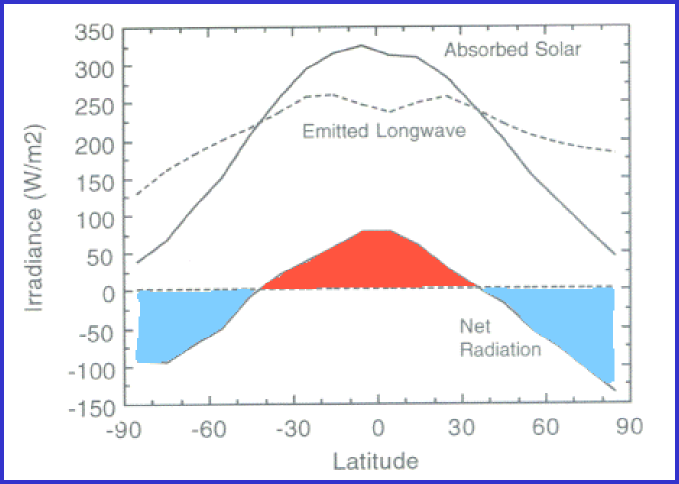


(from *Meteorology: Understanding the Atmosphere*)

- Polarward heat flux is needed to transport radiation energy from the tropics to higher latitudes.

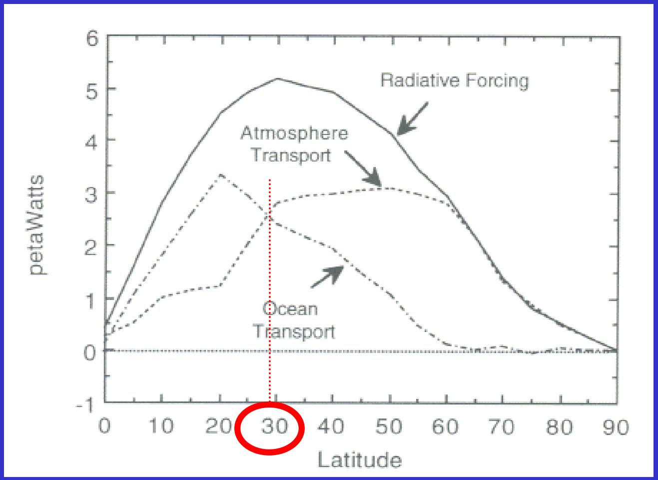
Polarward Energy Transport

Annual-Mean Radiative Energy



Polarward heat flux is needed to transport radiative energy from the tropics to higher latitudes

Polarward Heat Flux



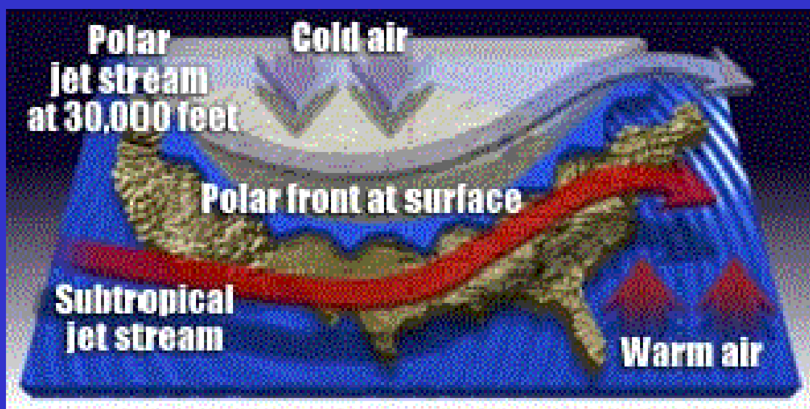
The atmosphere dominates the polarward heat transport at middle and high latitudes. The ocean dominates the transport at lower latitudes.

(figures from *Global Physical Climatology*)

(1 petaWatts = 10^{15} W)

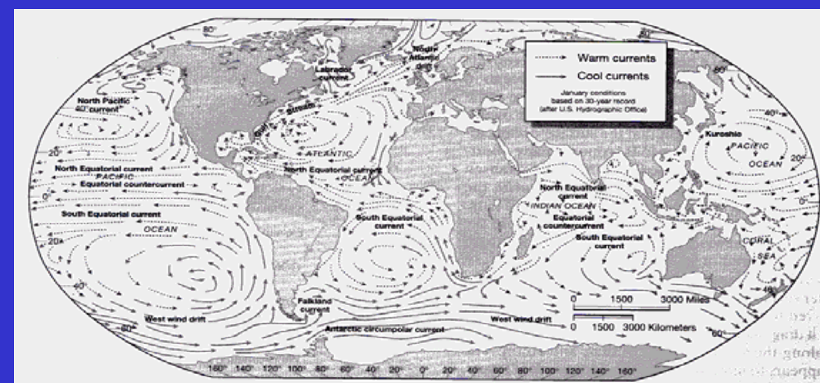
How Do Atmosphere and Ocean Transport Heat?

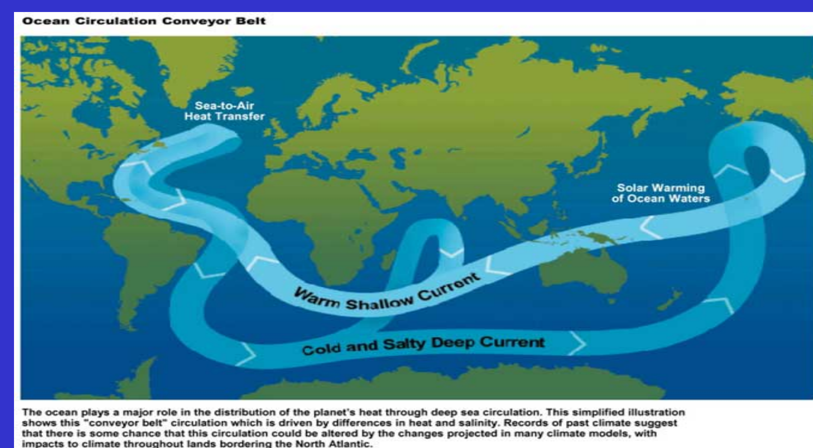
Atmospheric Circulation



(from USA Today)

Ocean Circulation





(top from *The Earth System*)
(bottom from USGCRP)

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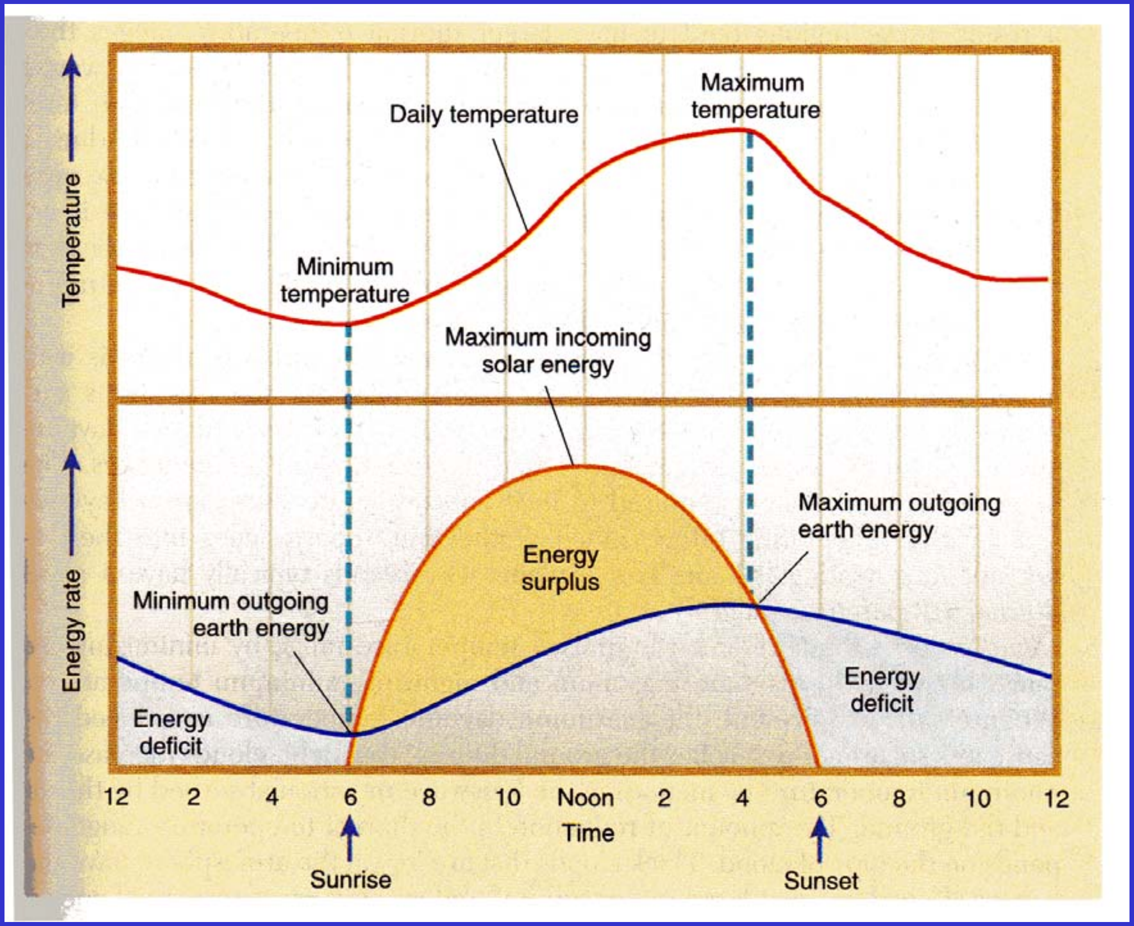
Diurnal Temperature Variations



(from *Meteorology: Understanding the Atmosphere*)