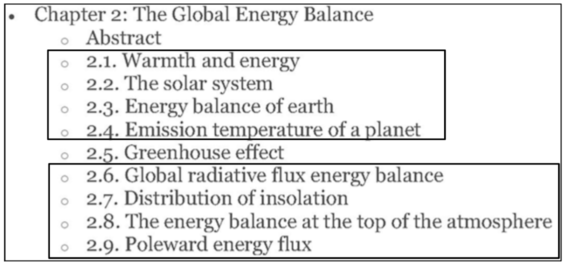
Lecture 2: The Global Energy Cycle



- Chapter 2: The Global Energy Balance
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  - 2.3. Energy balance of earth
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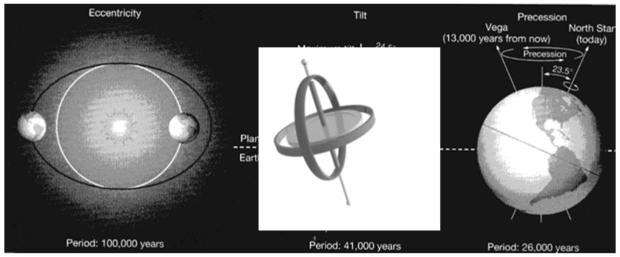
  - 2.9. Poleward energy flux

❑ Planetary energy balance

❑ Greenhouse Effect

❑ Vertical and latitudinal energy balance

Earth's Orbit and Its Variations



(from *The Earth System*)

❑ First, Earth spins around on its axis once every day ➔ The ***Tilt.***

❑ Second, Earth revolves around the Sun once a year ➔ The shape of the ***Orbit***.

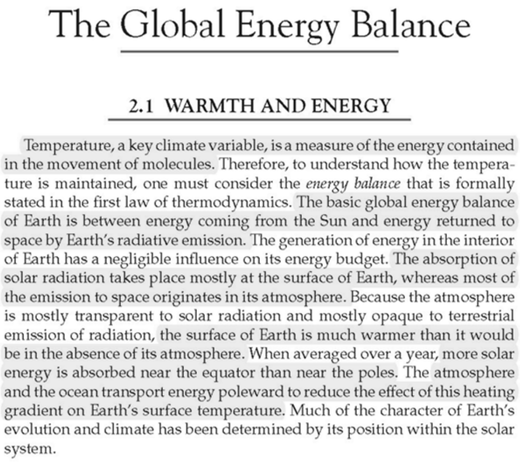
❑ Both the tilt and the shape of the orbit have changed over time and produce three types of orbital variations:

(1) obliquity variations

(2) eccentricity variations

(3) precession of the spin axis.

You Need to Know Why:



The Global Energy Balance

2.1 WARMTH AND ENERGY

Temperature, a key climate variable, is a measure of the energy contained in the movement of molecules. Therefore, to understand how the temperature is maintained, one must consider the *energy balance* that is formally stated in the first law of thermodynamics. The basic global energy balance of Earth is between energy coming from the Sun and energy returned to space by Earth's radiative emission. The generation of energy in the interior of Earth has a negligible influence on its energy budget. The absorption of solar radiation takes place mostly at the surface of Earth, whereas most of the emission to space originates in its atmosphere. Because the atmosphere is mostly transparent to solar radiation and mostly opaque to terrestrial emission of radiation, the surface of Earth is much warmer than it would be in the absence of its atmosphere. When averaged over a year, more solar energy is absorbed near the equator than near the poles. The atmosphere and the ocean transport energy poleward to reduce the effect of this heating gradient on Earth's surface temperature. Much of the character of Earth's evolution and climate has been determined by its position within the solar system.

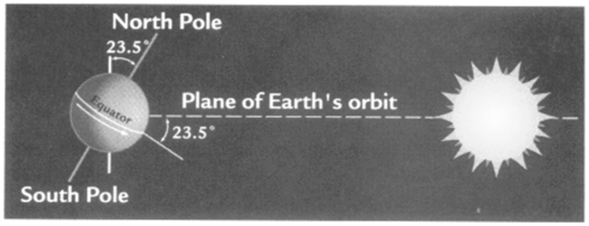
Orbit and Insolation

❑ Variations in the eccentricity of the orbit cause changes in the annually averaged amount of sunlight hitting Earth.

❑ Variations in the tilt (obliquity variations and the precession of the tilt) do not affect the averaged amount of solar radiation to the Earth.

❑ The tilt variations affect seasons.

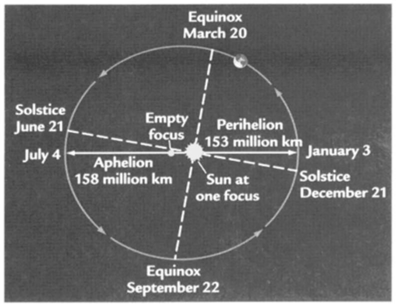
How Does the Tilt Affect Climate?



(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***!!

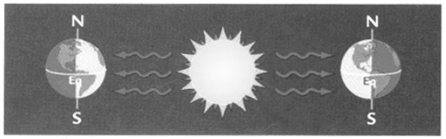
How Does Orbit's Shape Affect Climate



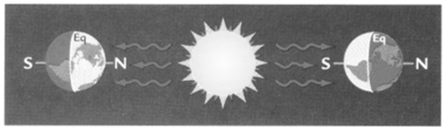
(from *Earth's Climate: Past and Future*)

- ❑ Earth's orbit is not a perfect circle: it has a slightly eccentric or elliptical shape.
- ❑ This noncircular shape is the result of the gravitational pull on Earth from the Sun, the moon, other planets and their moons.
- ❑ The distance to the Sun changes with Earth's position in its orbit.
- ❑ This changing distance has a direct effect on the amount of solar energy Earth receives.

Tilt Creates Seasons



A No tilt

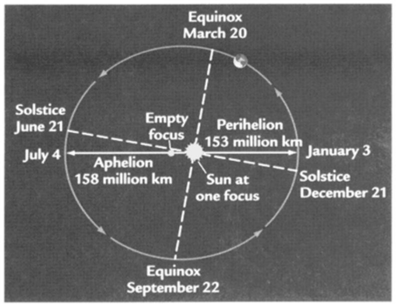


B 90° tilt

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

- ❑ Assume the Earth has a perfectly circular orbit around the Sun.
- ❑ With no tilt, incoming solar radiation is always directed straight at the equator throughout the year.
- ❑ With no tilt, no seasonal changes occur in solar radiation received at any latitude.
- ❑ As a result, solstices and equinoxes do not even exit ➔ NO SEASONS!

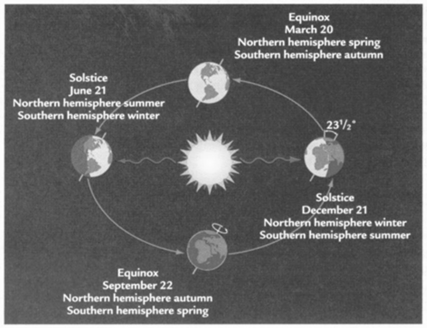
Perihelion and Aphelion



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

- ❑ The position in which the Earth is closest to the Sun is called "perihelion".
- ❑ Perihelion means "near the Sun" in Greek.
- ❑ The position in which the Earth is farthest to the Sun is called "aphelion".
- ❑ Aphelion means "away from the Sun" in Greek.

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].)

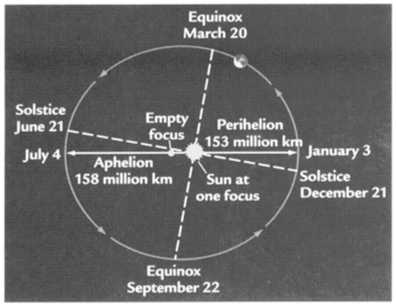
- ❑ Seasons

  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.

Seasonal Temperature Contrast



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

- ❑ The seasonal temperature contrast is referred to the range of temperature extremes between summer and winter.
- ❑ The combination of an eccentric orbit and a tilted spin axis means that the seasonal temperature contrast is different in the Southern and Northern Hemispheres.
- ❑ The Southern Hemisphere experiences a larger seasonal temperature contrast than the Northern Hemisphere.

Solar Flux and Flux Density

- ❑ Solar Luminosity (***L***)

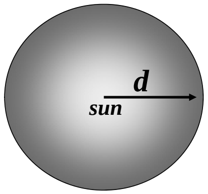
  the constant flux of energy put out by the sun

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

- ❑ Solar Flux Density (solar irradiance) (S_d)

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

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



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)

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

Solar Energy Incident On the Earth

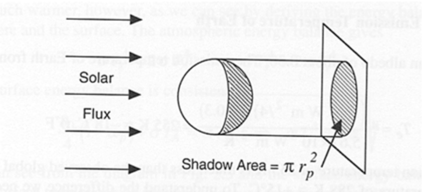
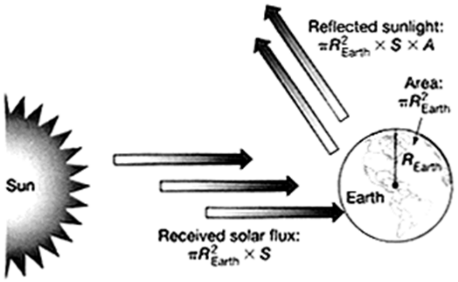


Fig. 2.2 Diagram showing the shadow area of a spherical planet.

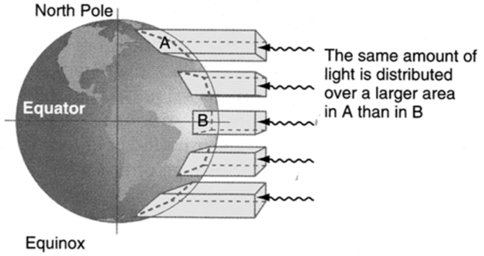
- ❑ Solar energy incident on the Earth
  - = total amount of solar energy **can be** absorbed by Earth
  - = (Solar constant) x (Shadow Area)
  - = $\boldsymbol{S \times \pi R^2_{Earth}}$

Albedo = [Reflected] / [Incoming] Sunlight



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

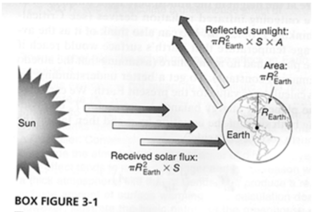
Zenith Angle and Insolation



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

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

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.

Stefan-Boltzmann Law

$$\boxed{E = \sigma T^4}$$

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 determines 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.

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.

Apply Stefan-Boltzmann Law To Sun and Earth

- **Sun**

  $E_s = (5.67 \text{ x } 10^{-8} \text{ W/m}^2 \text{ K}^4) * (6000\text{K})^4$
  $= 73{,}483{,}200 \text{ W/m}^2$

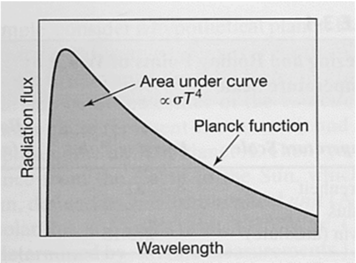
- **Earth**

  $E_e = (5.67 \text{ x } 10^{-8} \text{ W/m}^2 \text{ K}^4) * (300\text{K})^4$
  $= 459 \text{ W/m}^2$

- 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**

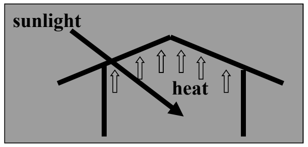
  The energy flux emitted by a blackbody is related to the fourth power of the body's absolute temperature

  $\mathbf{F = \sigma T^4}$ where σ is 5.67×10^{-8} W/m²/K

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

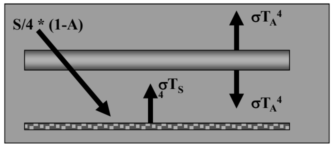
Greenhouse Effect

Greenhouse



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

Atmosphere



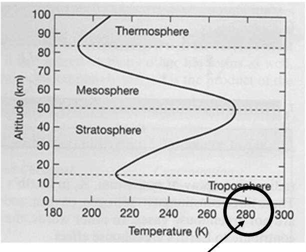
❑ For Earth's surface:
$S/4*(1-A) + \sigma T_A^4 = \sigma T_S^4$

❑ For the atmosphere:
$\sigma T_S^4 = 2\sigma T_A^4$

➔ $\mathbf{T_A = T_e = 255K}$

➔ $\mathbf{T_s = 2^{1/4}\, T_A = 303K}$

Planetary Energy Balance



(from *Global Physical Climatology*)

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

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

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

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

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

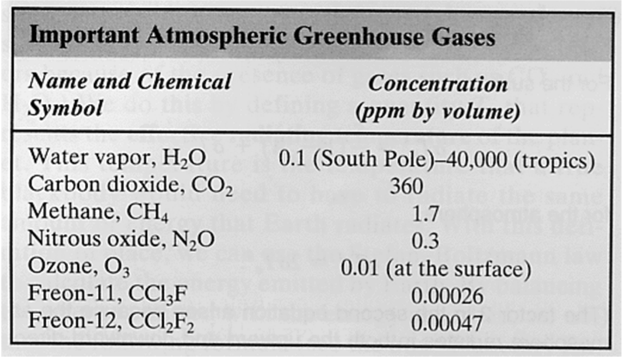
$$= 240 \text{ W/m}^2$$

Earth's *surface* temperature
T_S = 288 K (15C)

- **Earth's *blackbody* temperature**
  T_e = 255 K (-18C)

greenhouse effect (33C) !!

Greenhouse Gases

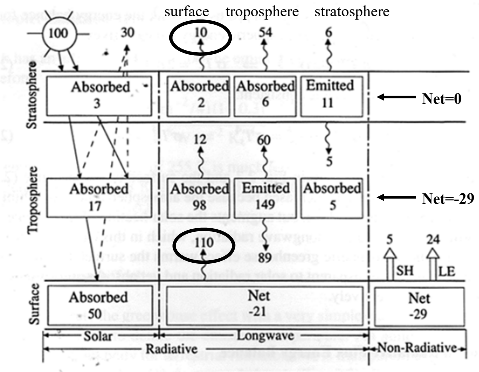


Important Atmospheric Greenhouse Gases

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

Vertical View of the Energy Balance

Vertical Distribution of Energy

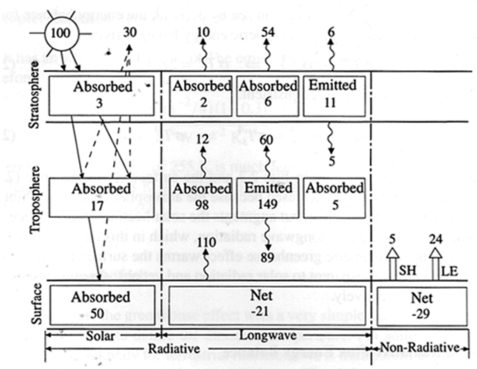


(from *Global Physical Climatology*)

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

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

Greenhouse Effect and Diurnal Cycle

- ❑ The very strong downward emission of terrestrial radiation from the atmosphere is crucial to maintain 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.

Energy Balance at the Top of Atmosphere (TOA)

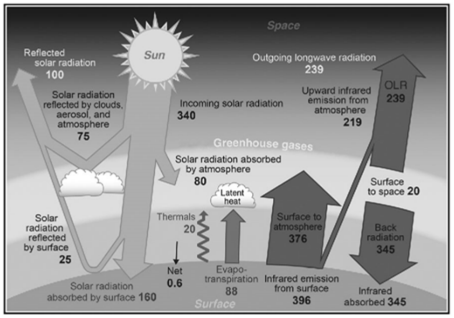


FIGURE 2.4 **Global and annual average radiative and nonradiative energy-flow diagram for Earth and its atmosphere.** Units are Wm^{-2}.

(from Global Physical Climatology)

- At the top of the atmosphere, absorbed solar radiation is about 240 Wm^{-2} and emitted terrestrial radiation is about 239 Wm^{-2}.
- The difference of about 0.6 Wm^{-2} is being stored in the ocean, which is heating up at the present time as a result of human production of greenhouse gases.

Energy Balance at the Surface

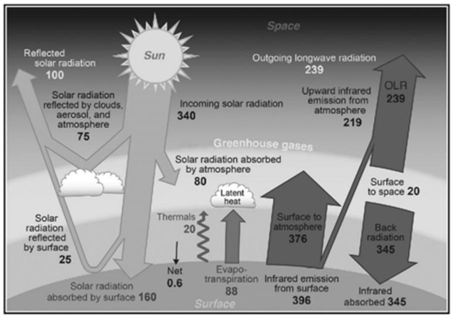


FIGURE 2.4 **Global and annual average radiative and nonradiative energy-flow diagram for Earth and its atmosphere.** Units are Wm^{-2}.

(from Global Physical Climatology)

- Although the surface receives 160 Wm^{-2} of solar radiation, this is less than half of the 345 Wm^{-2} that the surface receives as downward thermal emission from the atmosphere.
- The surface emits 396 Wm^{-2} of radiation upward, so that net sum of upward and downward terrestrial radiation cools the surface at a net rate of 51 Wm^{-2}.
- This rate of cooling is smaller than the sum of evaporation (88 Wm^{-2}) and convection of warmth away from the surface (20 Wm^{-2})..

Absorption of Solar Radiation

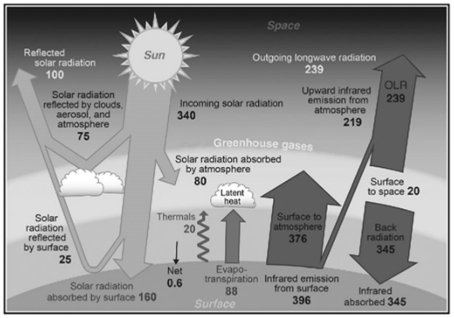
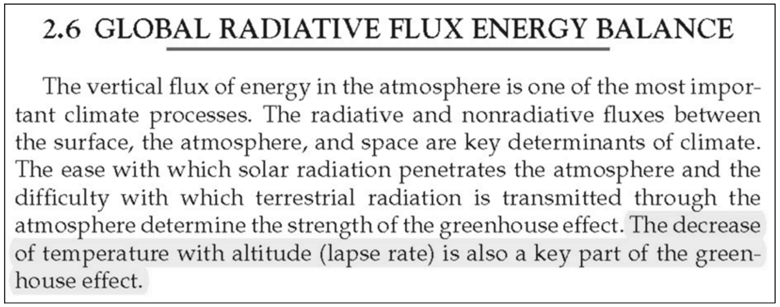


FIGURE 2.4 **Global and annual average radiative and nonradiative energy-flow diagram for Earth and its atmosphere.** Units are Wm^{-2}.

(from Global Physical Climatology)

- Of the 240 Wm^{-2} of solar radiation absorbed in the climate system, only about a third is absorbed in the atmosphere and two-thirds is absorbed at the surface.

Why?



2.6 GLOBAL RADIATIVE FLUX ENERGY BALANCE

The vertical flux of energy in the atmosphere is one of the most important climate processes. The radiative and nonradiative fluxes between the surface, the atmosphere, and space are key determinants of climate. The ease with which solar radiation penetrates the atmosphere and the difficulty with which terrestrial radiation is transmitted through the atmosphere determine the strength of the greenhouse effect. The decrease of temperature with altitude (lapse rate) is also a key part of the greenhouse effect.

What do We Learn from the Vertical Energy Balance?

- ❑ About 81% of the radiative cooling of the atmosphere is balanced by latent heating.

➔This marks a very significant constraint on the precipitation rate, since the heating of the atmosphere by the condensation of water vapor must be approximately balanced by the radiative cooling of the atmosphere.

- ❑ The very strong downward emission of terrestrial radiation from the atmosphere is essential for maintaining the relatively small diurnal variations in surface temperature over land.

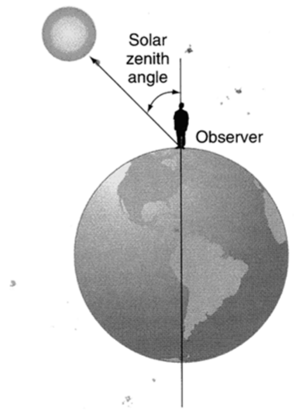
➔ If the downward longwave were not larger than the solar heating of the surface, then the land surface temperature would cool more rapidly at night, yielding a large diurnal variation of surface temperature.

Insolation

- ❑ ***Insolation is the amount of downward solar radiation energy incident on a plane surface***.
- ❑ Seasonal and latitudinal variations in temperature are driven primarily by variations of insolation and average ***solar zenith angle***.
- ❑ The amount of solar radiation incident on the top of the atmosphere depends on the latitude, season, and time of day.
- ❑ The amount of solar energy that is reflected to space without absorption depends on the solar zenith angle and the properties of the local surface and atmosphere.

Latitudinal View of the Energy Balance

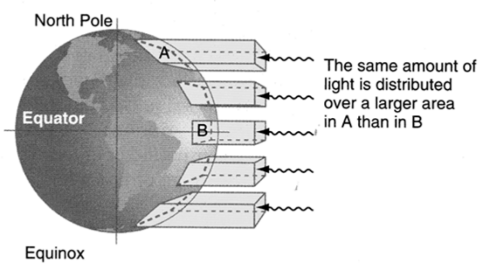
Solar Zenith Angle



- ❑ 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*)

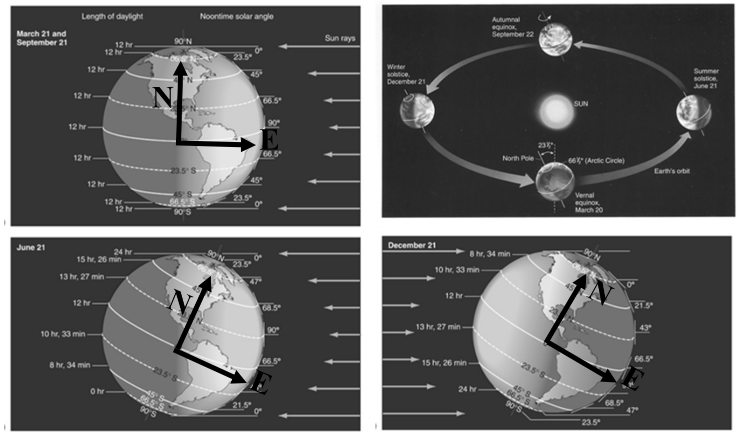
Zenith Angle and Insolation



(from *Meteorology: Understanding the Atmosphere*)

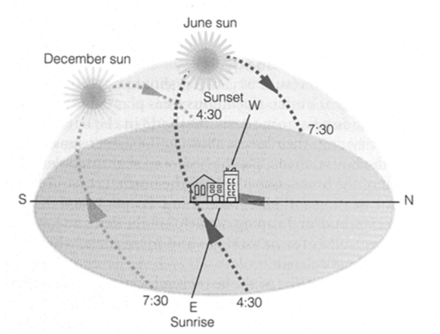
- ❑ The larger the solar zenith angle, the weaker the insolation, because the same amount of sunlight has to be spread over a larger area.

Length of Day



(from *Understanding Weather & Climate* and *Meteorology Today*)

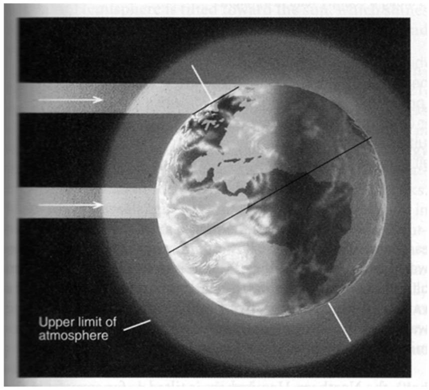
What Determine Zenith Angle?



(from *Meteorology Today)*

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

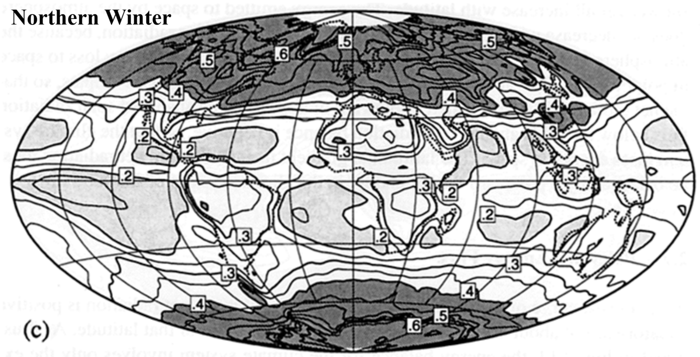
Solar Zenith Angle Affects Albedo



(from *Meteorology Today*)

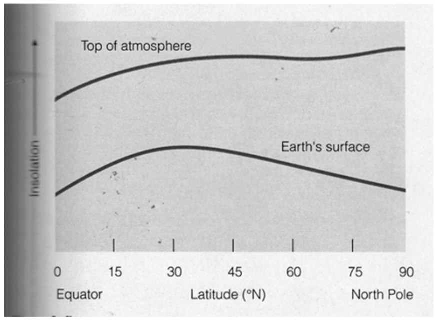
- ❑ The larger the solar zenith angle, the larger the albedo.
- ❑ When the zenith angle is large, sunlight has to pass through a thicker layer of the atmosphere before it reaches the surface.
- ❑ The thinker the atmospheric layer, more sunlight can be reflected or scattered back to the space.

Global Distribution of Albedo



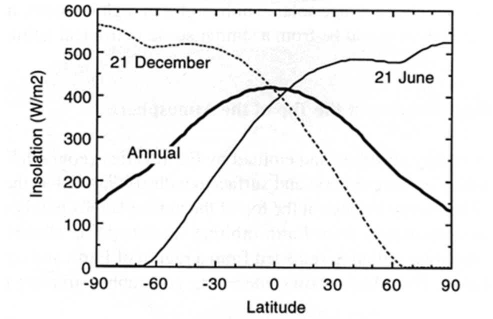
(from *Global Physical Climatology*)

Insolation in Summer Solstice



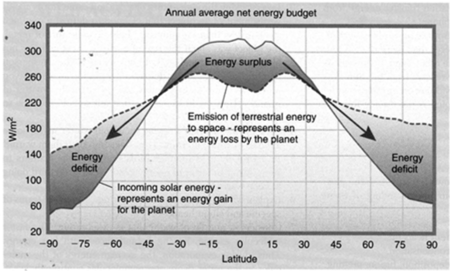
(from *Meteorology Today*)

Insolation at Top of Atmosphere



(from *Global Physical Climatology*)

Latitudinal Variations of Net Energy

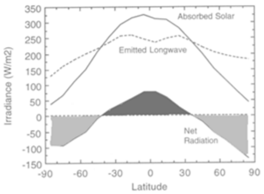


(from *Meteorology: Understanding the Atmosphere*)

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

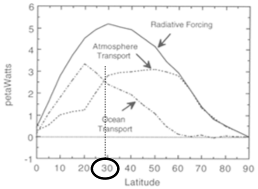
Polarward Energy Transport

Annual-Mean Radiative Energy



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

Polarward Heat Flux

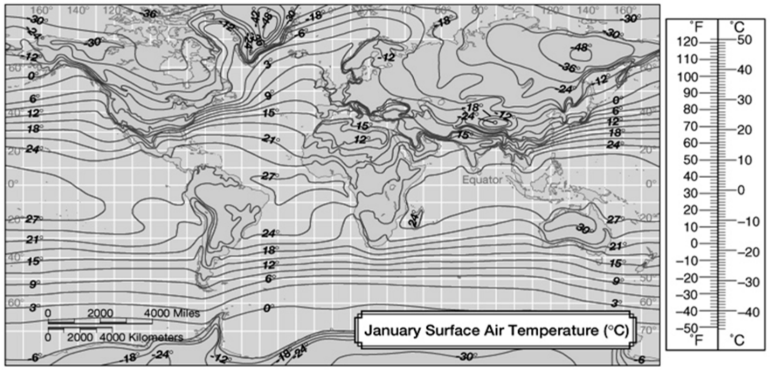


The atmosphere dominates the polarward heat transport at middle and high latitudes. The ocean dominates the transport at lower latitudes.

(1 petaWatts = 10^{15} W)

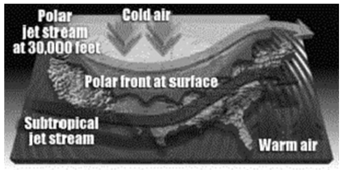
(figures from *Global Physical Climatology*)

Isotherm



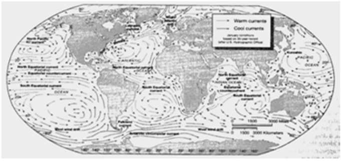
How Do Atmosphere and Ocean Transport Heat?

Atmospheric Circulation



(from USA Today)

Ocean Circulation



(from *The Earth System*)