Lecture 2: Global Energy Balance

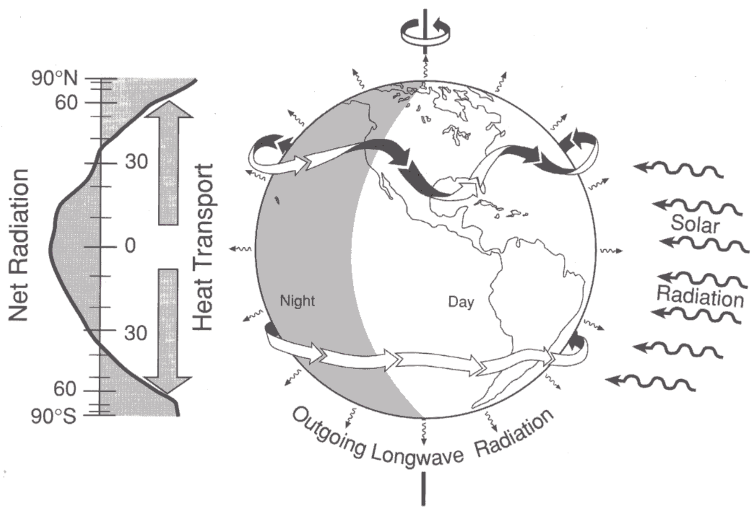


Figure 1.2: The incoming solar radiation (right) illuminates only part of the Earth while the outgoing long-wave radiation is distributed more evenly. On an annual mean basis, the result is an excess of absorbed solar radiation over the outgoing long-wave radiation in the tropics, while there is a deficit at middle to high latitudes (far left), so that there is a requirement for a poleward heat transport in each hemisphere (arrows) by the atmosphere and the oceans. This radiation distribution results in warm conditions in the tropics but cold at high latitudes, and the temperature contrast results in a broad band of westerlies in the extra-tropics of each hemisphere in which there is an embedded jet stream (shown by the "ribbon" arrows) at about 10 km above the Earth's surface. The flow of the jetstream over the different underlying surface (ocean, land, mountains) produces waves in the atmosphere and adds geographic spatial structure to climate. The excess of net radiation at the equator is 68 Wm^{-2} and the deficit peaks at -100 Wm^{-2} at the South Pole and -125 Wm^{-2} at the North Pole; from Trenberth and Solomon (1994).

(from *Climate Change 1995*)

- **Planetary energy balance**

  Energy absorbed by Earth = Energy emitted by Earth

- **Role of the atmosphere**

  Greenhouse effect

- **Role of oceans**

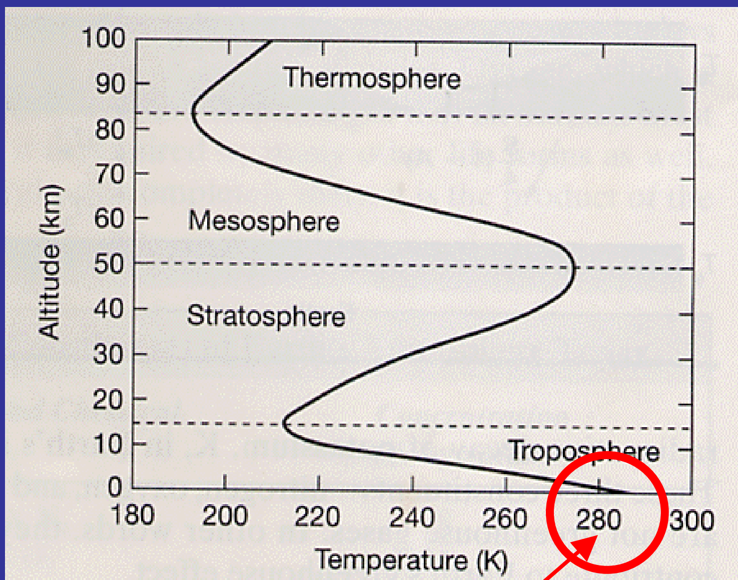
  Polarward energy transport

- **Role of land surface**

  not significant due to its low heat capacity

Global View of the Energy Balance

Planetary Energy Balance



(from *Global Physical Climatology*)

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

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

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

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

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

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

Earth's *surface* temperature

T_S = 288 K (15C)

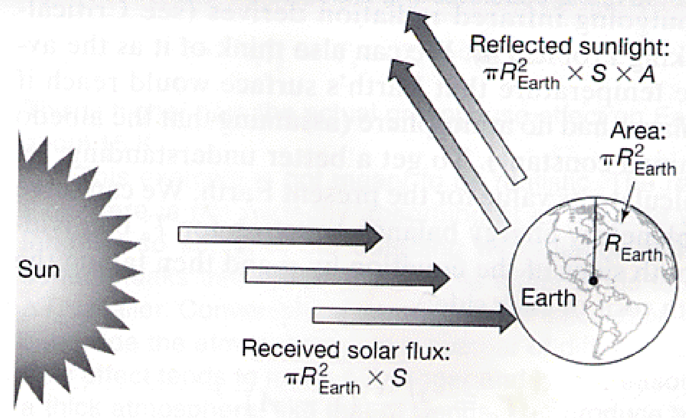
- **Earth's *blackbody* temperature**

T_e = 255 K (-18C)

greenhouse effect (33C) !!

ESS200A
Prof. Jin-Yi Yu

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.

Solar Energy Incident On the Earth

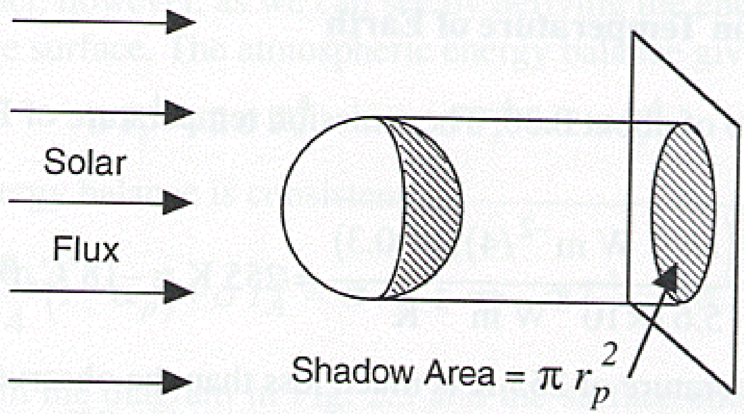


Fig. 2.2 Diagram showing the shadow area of a spherical planet.

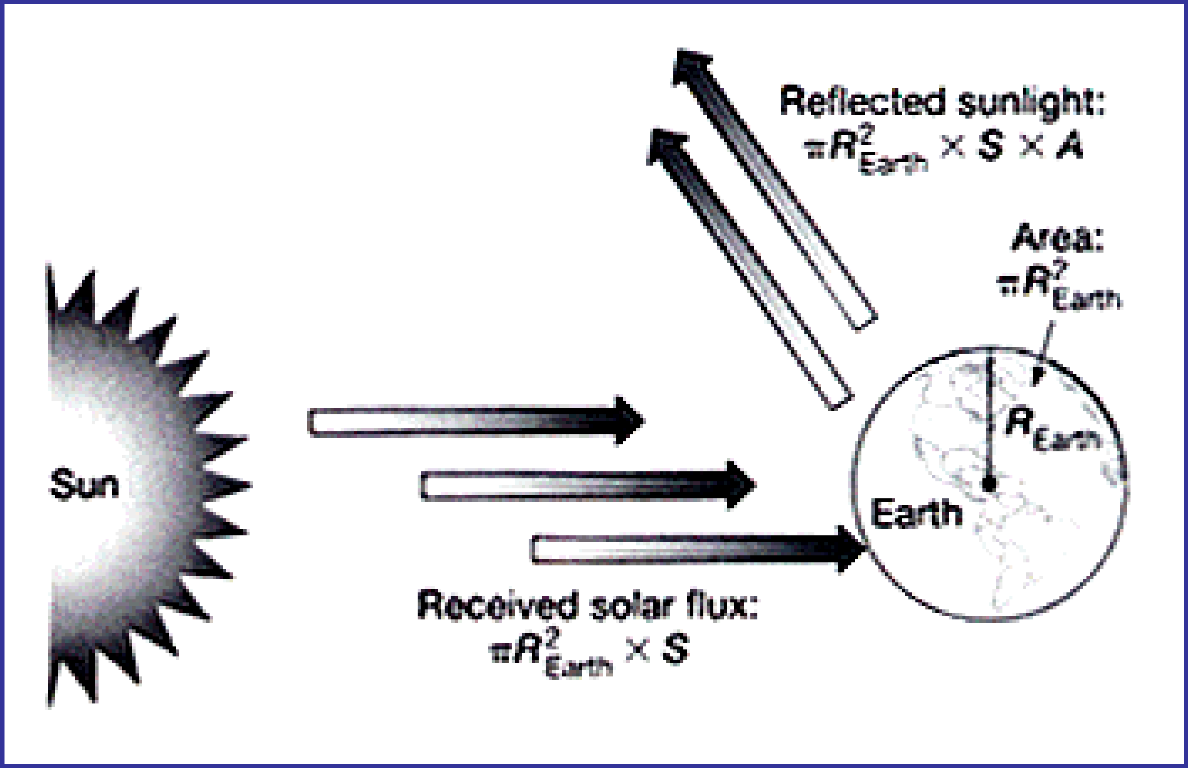
- Solar energy incident on the Earth

  = total amount of solar energy **can be** absorbed by Earth

  = (Solar constant) x (Shadow Area)

  = $S \times \pi R^2_{Earth}$

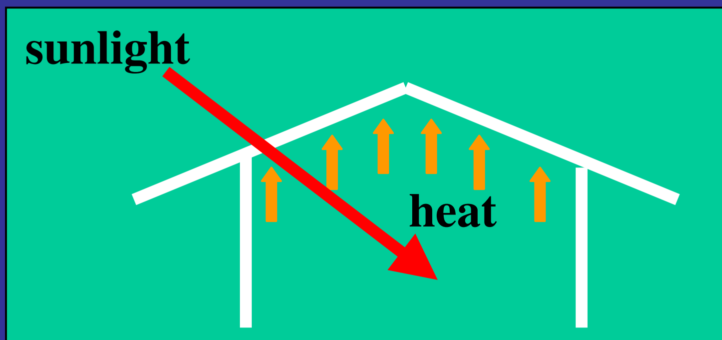
Albedo = [Reflected] / [Incoming] Sunlight



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

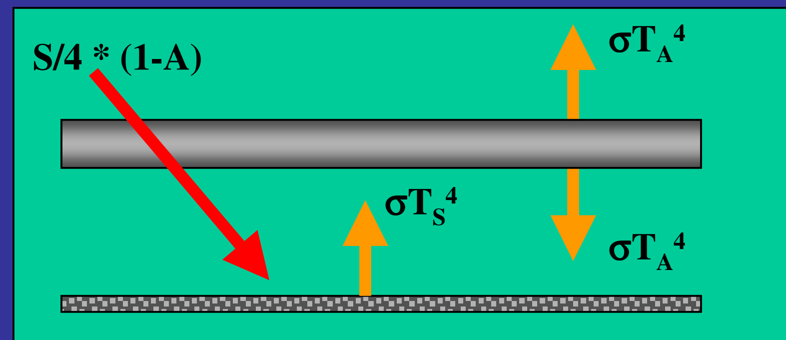
Greenhouse Effect

Greenhouse



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

Atmosphere



For the atmosphere:

$2^* \sigma T_A^4 = \sigma T_S^4 \rightarrow T_A = 2^{**}¼ \; T_e$

For Earth's surface:

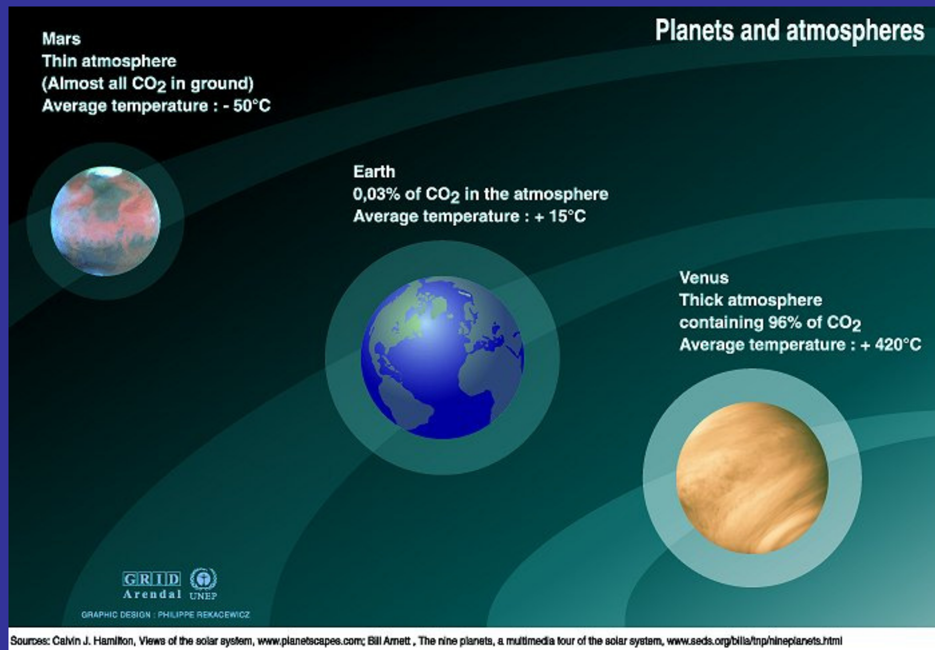
$S/4^*(1\text{-}A) + \sigma T_A^4 = \sigma T_S^4$

$\rightarrow$ **T_S = 303K**

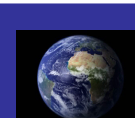
Three Factors To Determine Planet Temperature

- Distance from the Sun
- Albedo
- Greenhouse effect

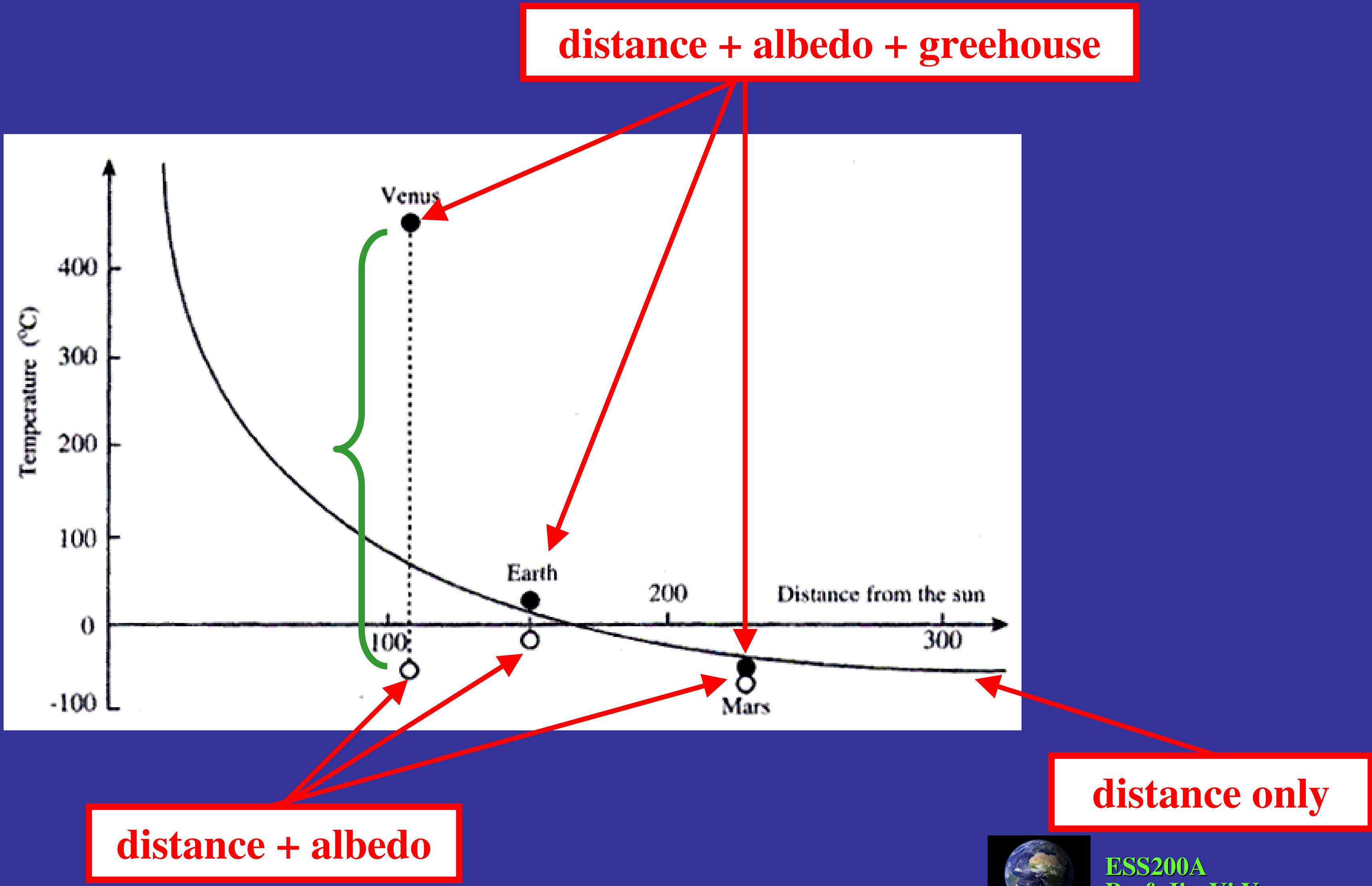
Earth, Mars, and Venus



Planet	Distance to the Sun	Radius	Planetary Albedo	Mean Surface Temperature
Venus	0.72 AU	6,051 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



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 too 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 water left on Venus (and no more chemical weathering)**

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

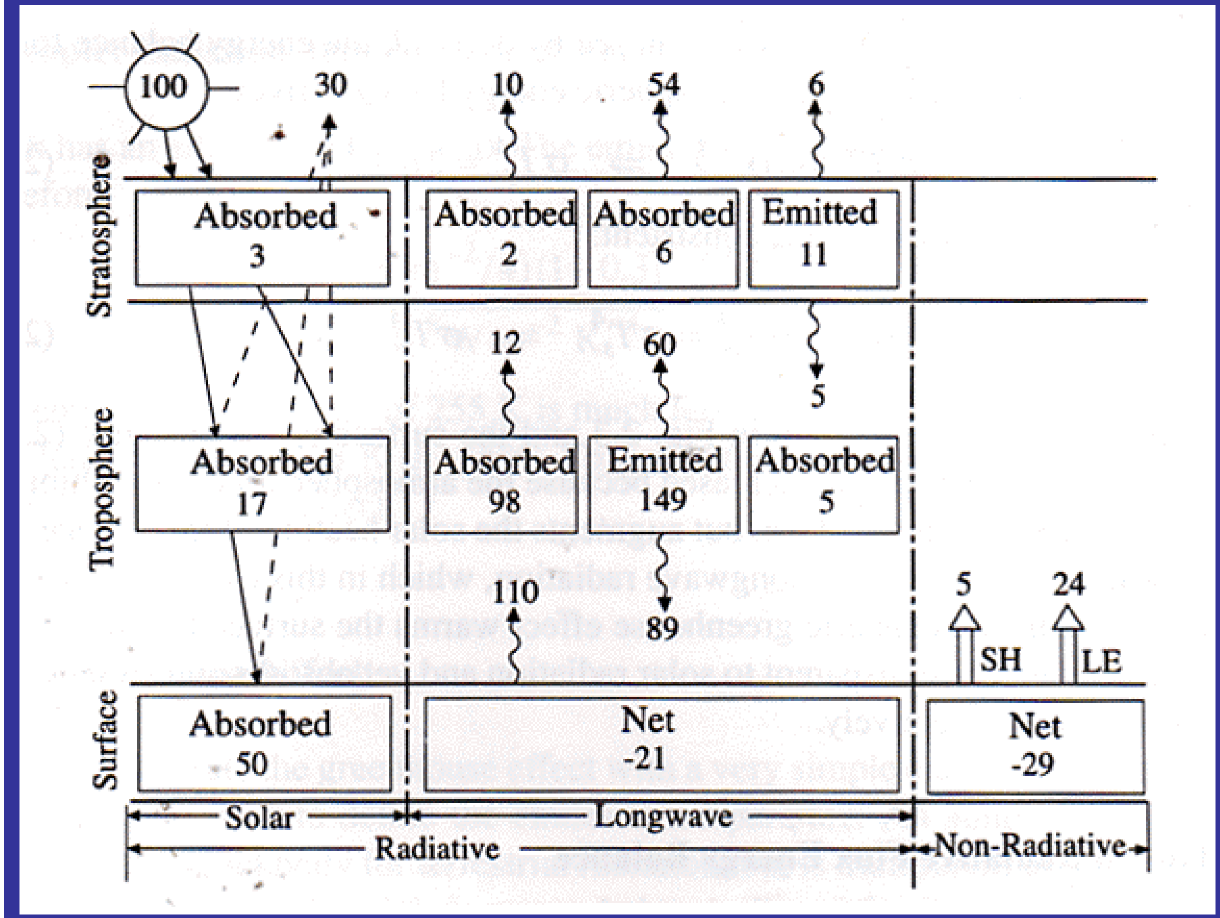
➔ Carbon can not be injected back to the atmosphere

➔ Little greenhouse effect

➔ **A very cold Mars!!**

Vertical View of the Energy Balance

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)

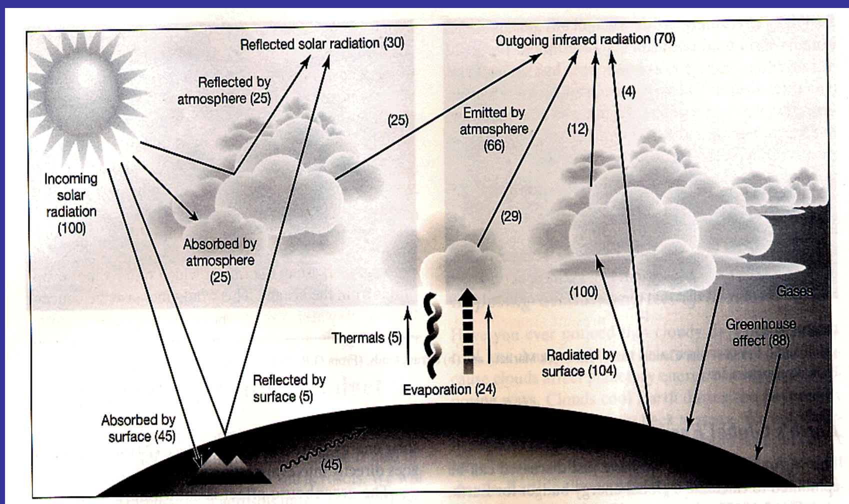
- 30% reflected/scattered back

  20% by clouds

  6% by the atmosphere

  4% by surface

Where Is Earth's Radiation Emitted From?



(from *The Earth System*)

Radiation back to Space (70 Units)

- 70 (units) radiation back to space

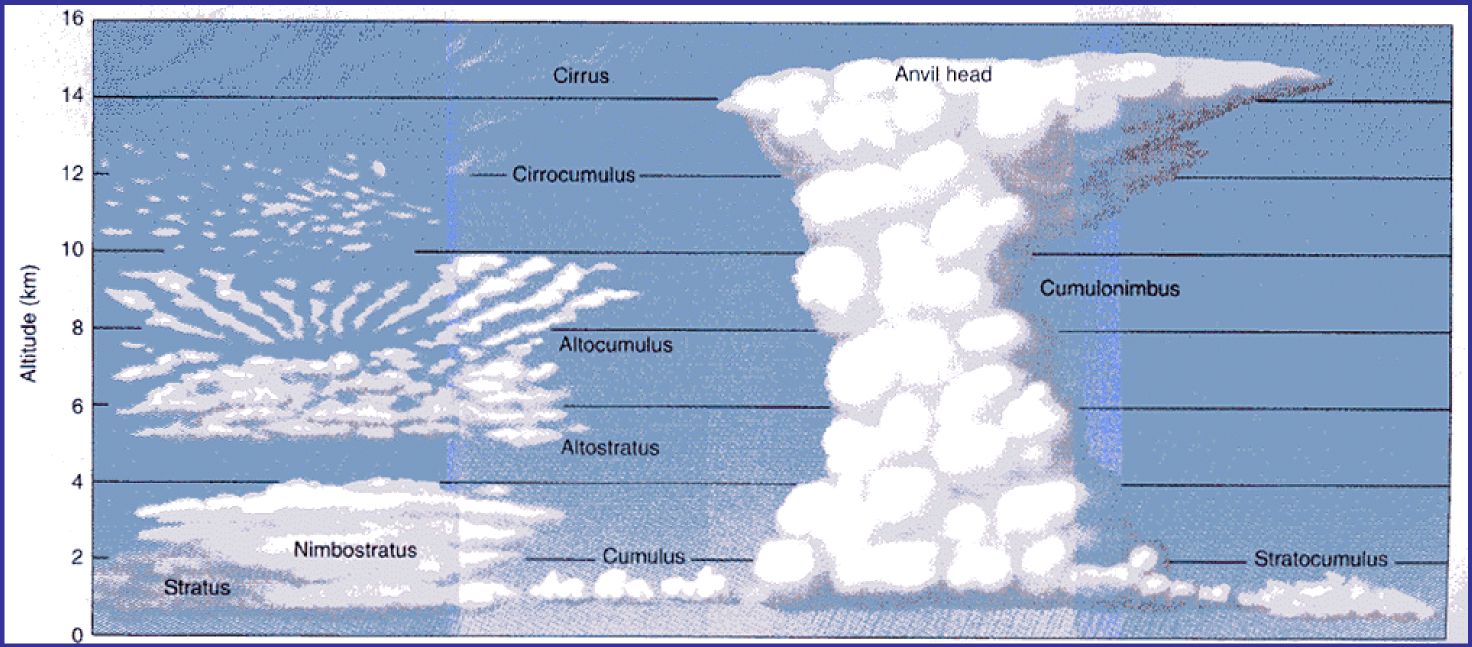
  60% by the atmosphere

  10% by surface (through clear sky)

- Greenhouse emission (back to surface)

  89% (of solar radiation)

Cloud Types Based On Height



If based on cloud base height, the ten principal cloud types can then grouped into four cloud types:

✓ High clouds -- cirrus, cirrostratus, cirroscumulus.

✓ Middle clouds – altostratus and altocumulus

✓ Low clouds – stratus, stratocumulus, and nimbostartus

✓ Clouds with extensive vertical development – cumulus and cumulonimbus.

(from "*The Blue Planet*")

Cloud Type Based On Properties

- Four basic cloud categories:
  - ✓ Cirrus --- thin, wispy cloud of ice.
  - ✓ Stratus --- layered cloud
  - ✓ Cumulus --- clouds having vertical development.
  - ✓ Nimbus --- rain-producing cloud

- These basic cloud types can be combined to generate ***ten different cloud types***, such as cirrostratus clouds that have the characteristics of cirrus clouds and stratus clouds.

Important Roles of Clouds In Global Climate

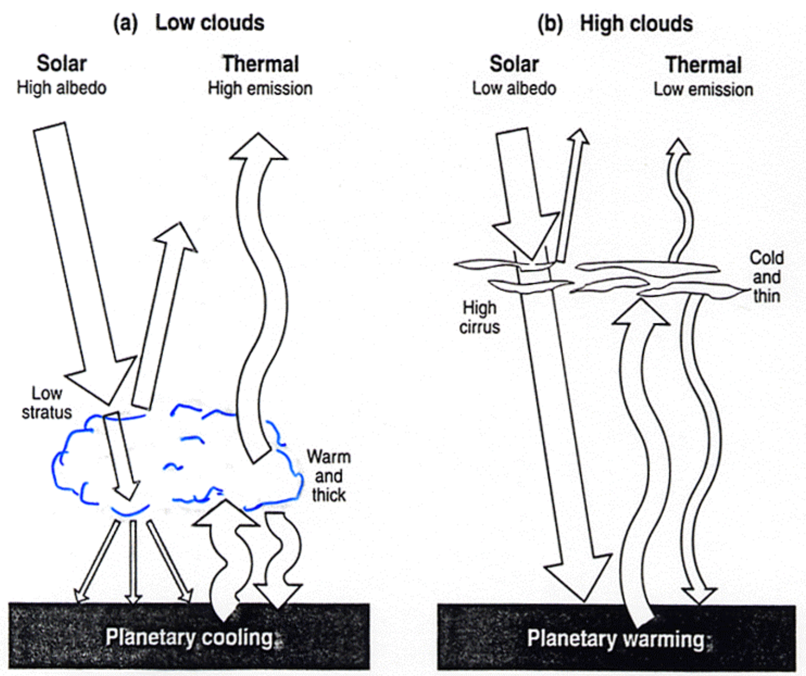
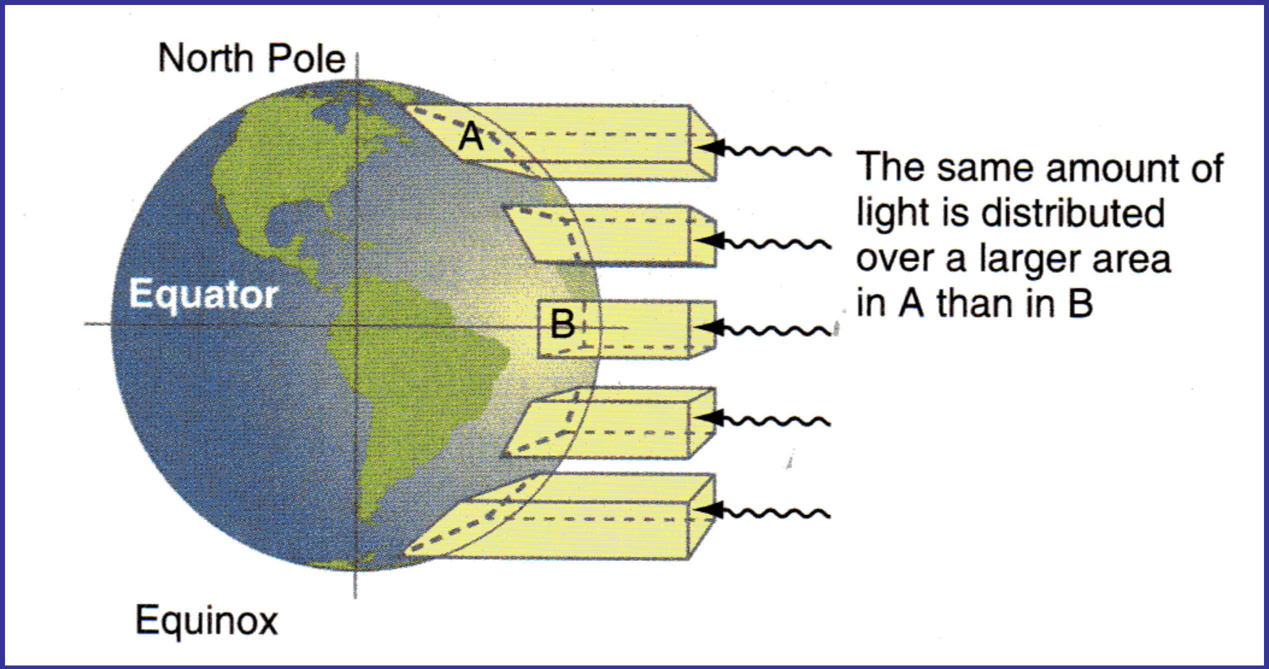


Figure 11.13 The effects of clouds on the flow of radiation and energy in the lower atmosphere and at the surface. Two cases are shown: (a) low clouds, with a high solar albedo and high thermal emission temperature; and (b) high clouds, with a low solar albedo and low thermal emission temperature. The solar components are shown as straight arrows, and the infrared components, as curved arrows. The relative thicknesses of the arrows indicate the relative radiation intensities. The expected impact on surface temperature in each situation is noted along the bottom strip.

Latitudinal View of the Energy Balance

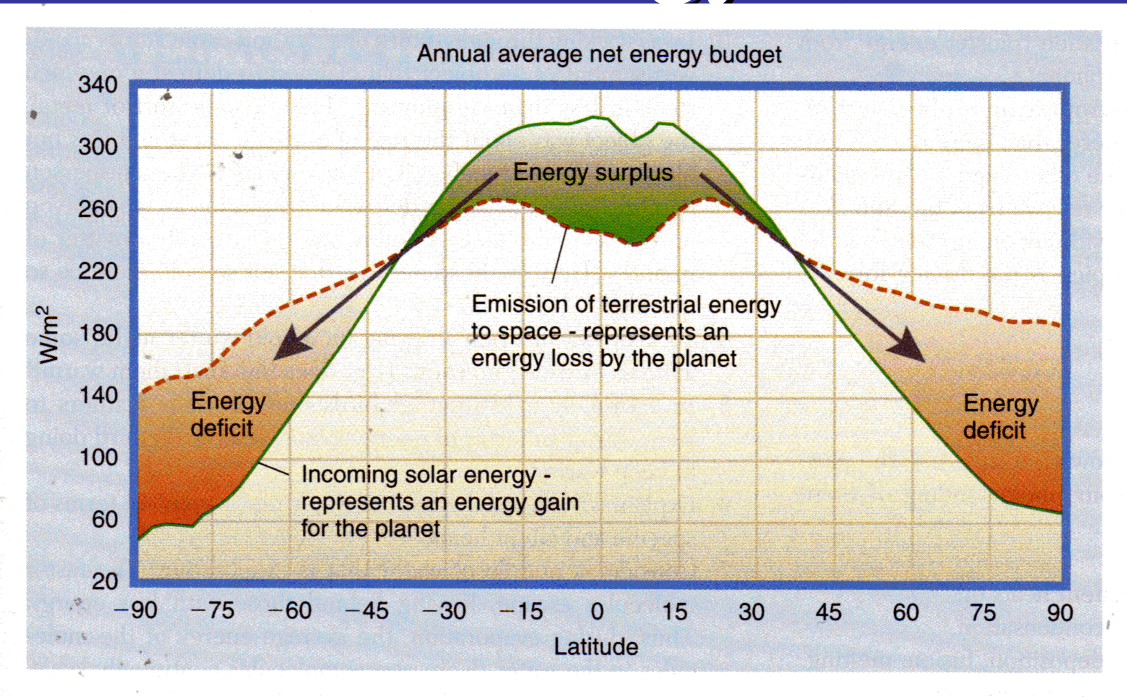
Zenith Angle and Insolation



(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.

Latitudinal Variations of Net Energy

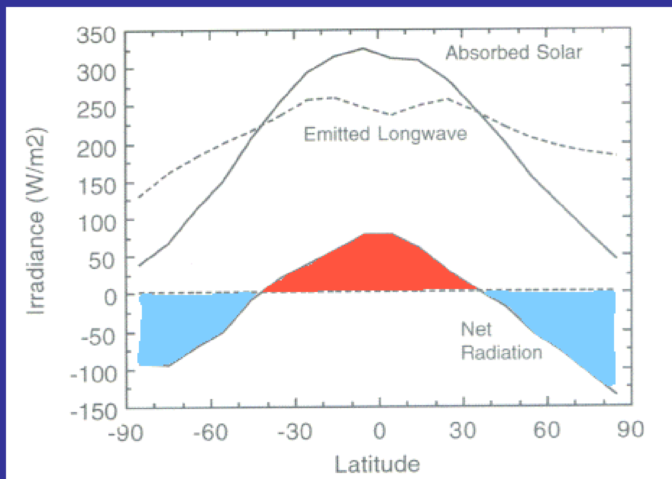


(from *Meteorology: Understanding the Atmosphere*)

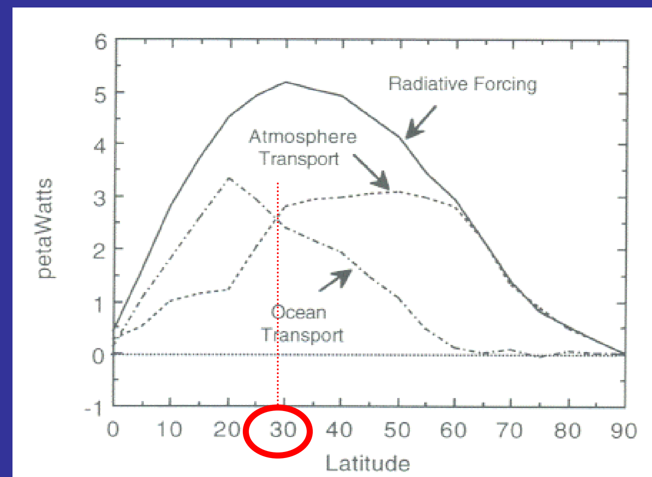
- Polarward heat flux is needed to transport radiation energy from the tropics to higher latitudes.

Polarward Energy Transport

Annual-Mean Radiative Energy



Polarward Heat Flux



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

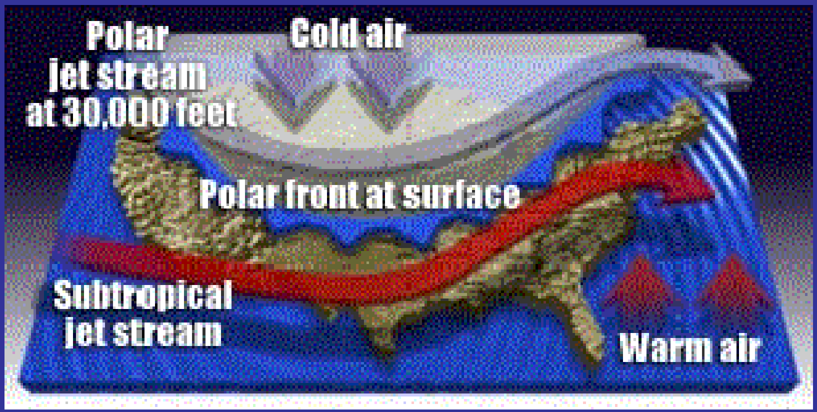
The atmosphere dominates the polarward heat transport at middle and high latitudes. The ocean dominates the transport at lower latitudes.

(1 petaWatts = 10^{15} W)

(figures from *Global Physical Climatology*)

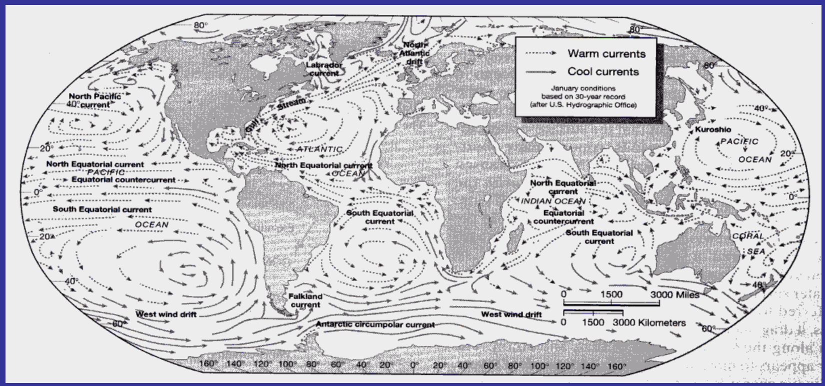
How Do Atmosphere and Ocean Transport Heat?

Atmospheric Circulation



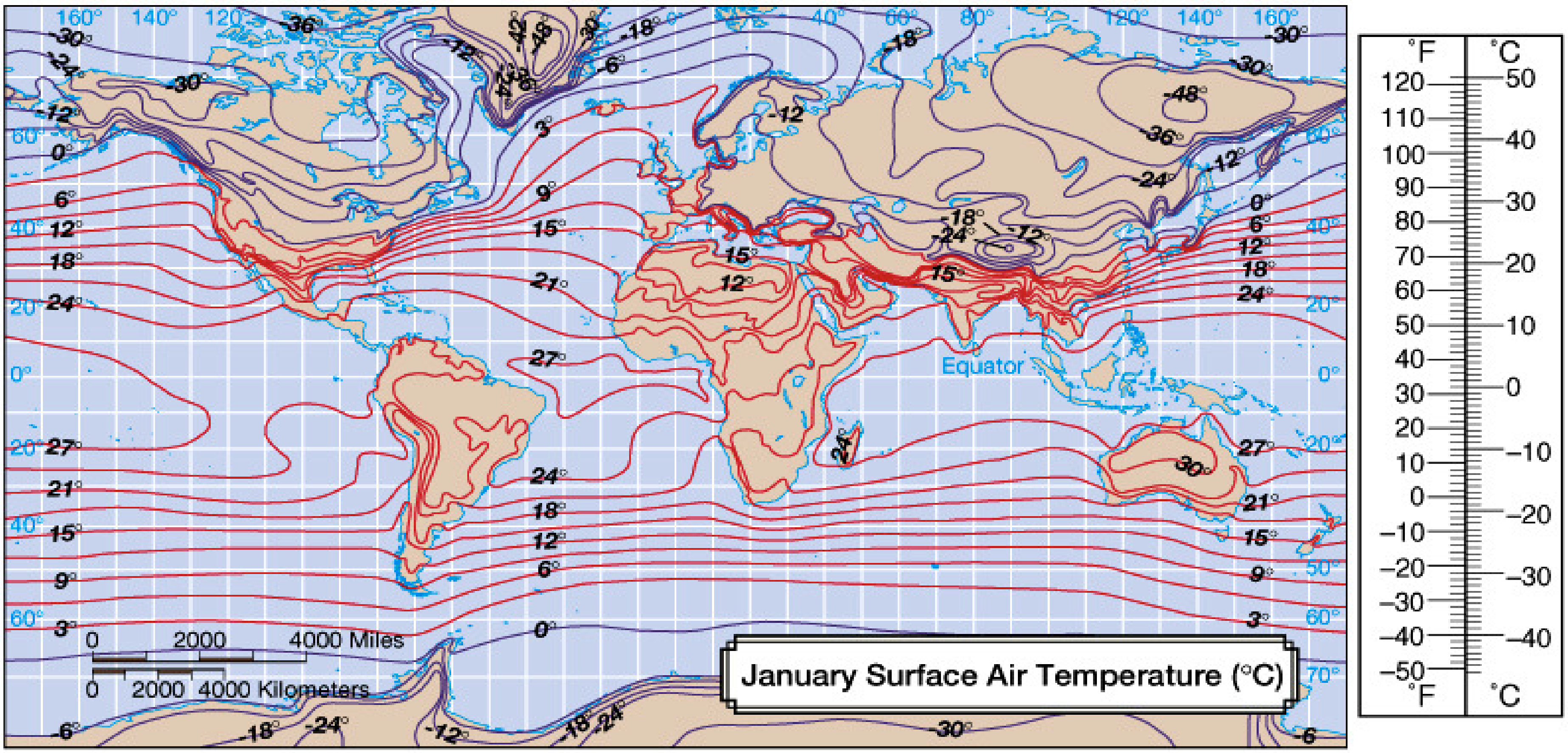
(from USA Today)

Ocean Circulation



(from *The Earth System*)

Isotherm


January Surface Air Temperature (°C)
Equator
0 2000 4000 Miles
0 2000 4000 Kilometers
°F
°C