Lecture 2: Global Energy Balance

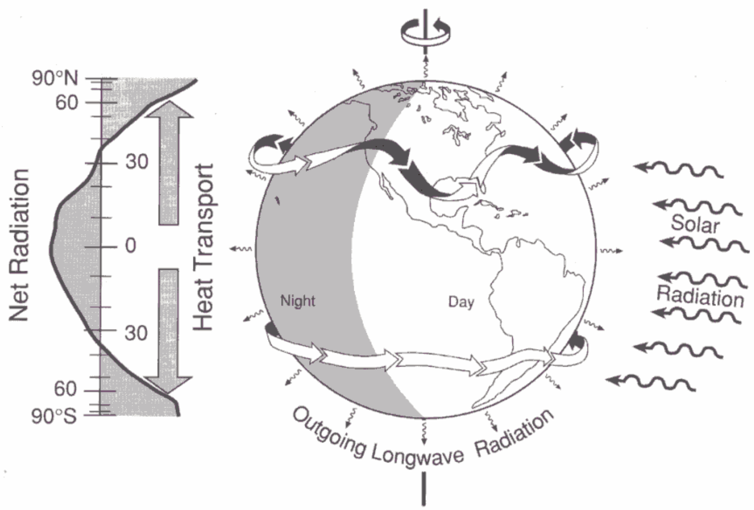


Figure 1.2: The incoming solar radiation (right) illuminates only part of the Earth while the outgoing long-wave radiation is distributed more evenly. On an annual mean basis, the result is an excess of absorbed solar radiation over the outgoing long-wave radiation in the tropics, while there is a deficit 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**

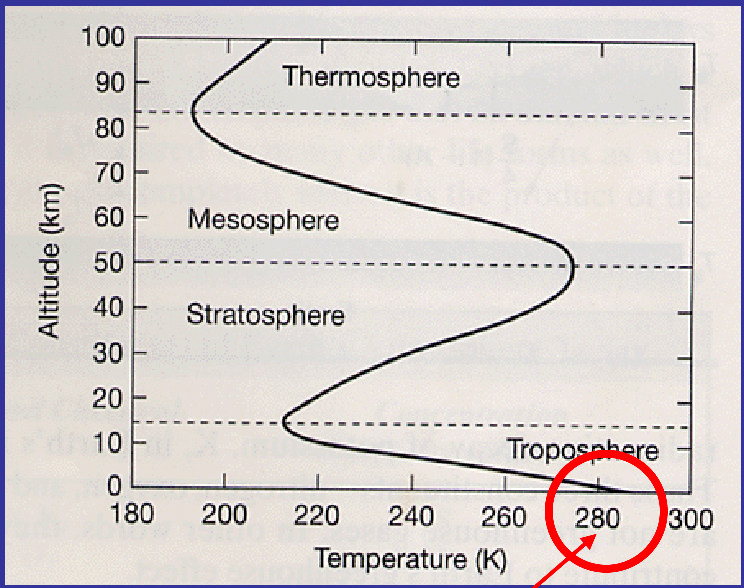
  Polarward energy transport

- **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**

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

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

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

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

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

Earth's *surface* temperature

T_S = 288 K (15C)

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

T_e = 255 K (-18C)

greenhouse effect (33C) !!

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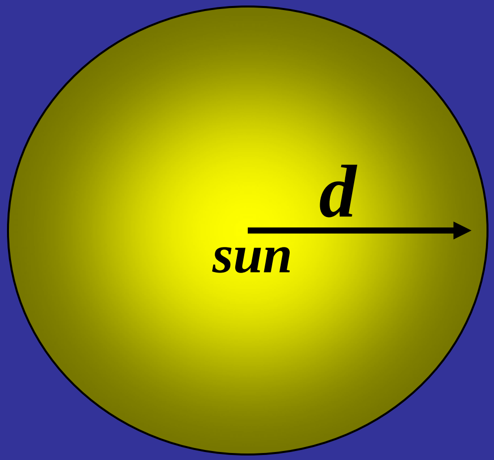
Solar Flux and Flux Density

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

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

- Solar Flux Density (S_d)
  the amount of solar energy per unit area on a sphere centered at the Sun with a distance ***d***



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

Solar Flux Density Reaching Earth

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

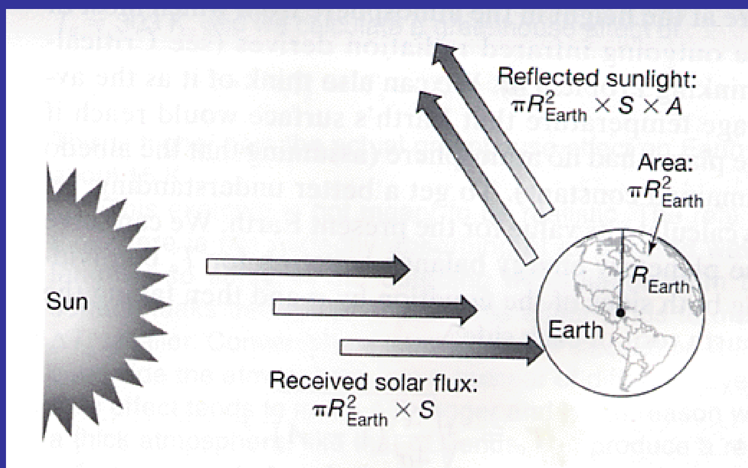
  The solar energy density at the mean distance of Earth from the sun (1.5×10^{11} m)

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

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

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

Solar Energy 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.

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Solar Energy Incident On the Earth

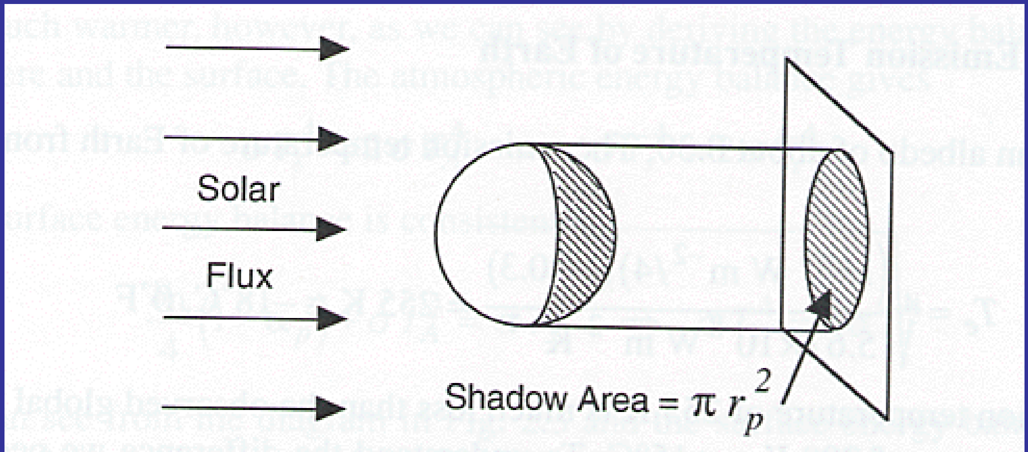


Fig. 2.2 Diagram showing the shadow area of a spherical planet.

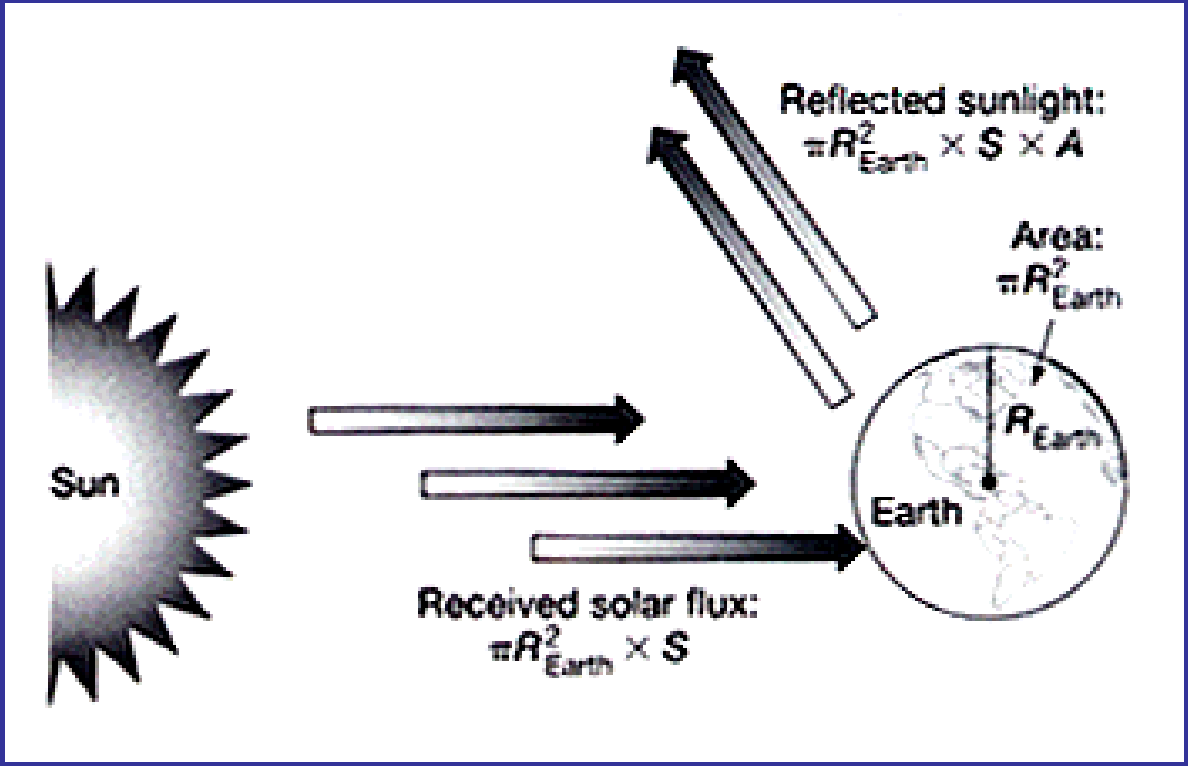
- Solar energy incident on the Earth

  = 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.

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

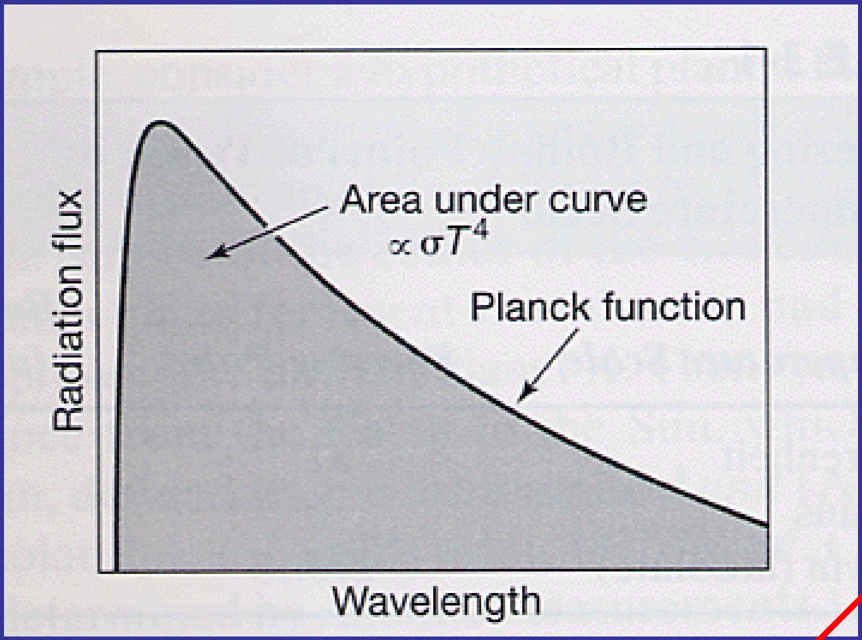
- Blackbody

  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*)

absolute temperature

- **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} $W/m^2/K^4$

- **Energy emitted from the Earth**

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

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

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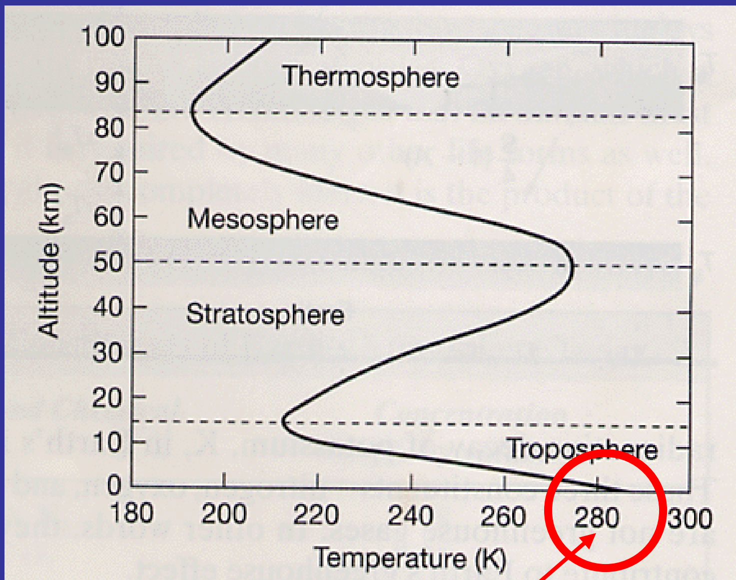
Planetary Energy Balance



(from *Global Physical Climatology*)

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Earth's *surface* temperature

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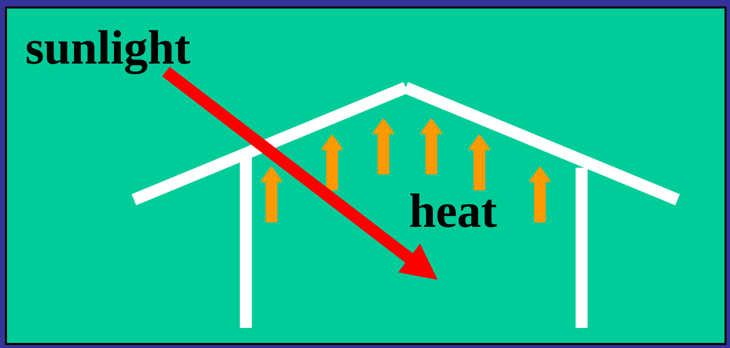
greenhouse effect (33C) !!

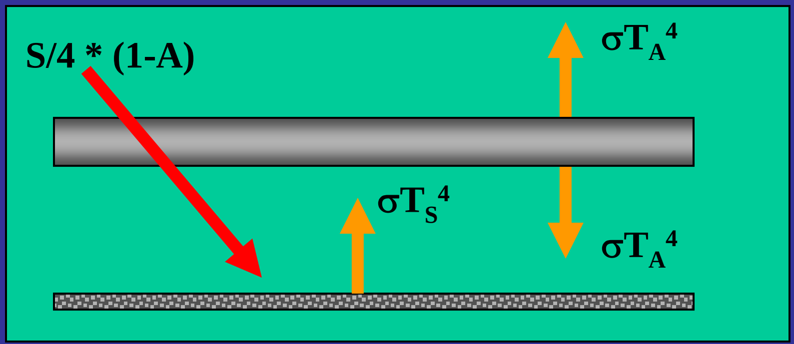
Greenhouse Effect

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**

Two Key Reasons for the Greenhouse Effect

- ❑ Solar and terrestrial radiations are emitted at very different wavelengths.

- ❑ The greenhouse gases selectively absorb certain frequencies of radiation.

Spectrum of Radiation

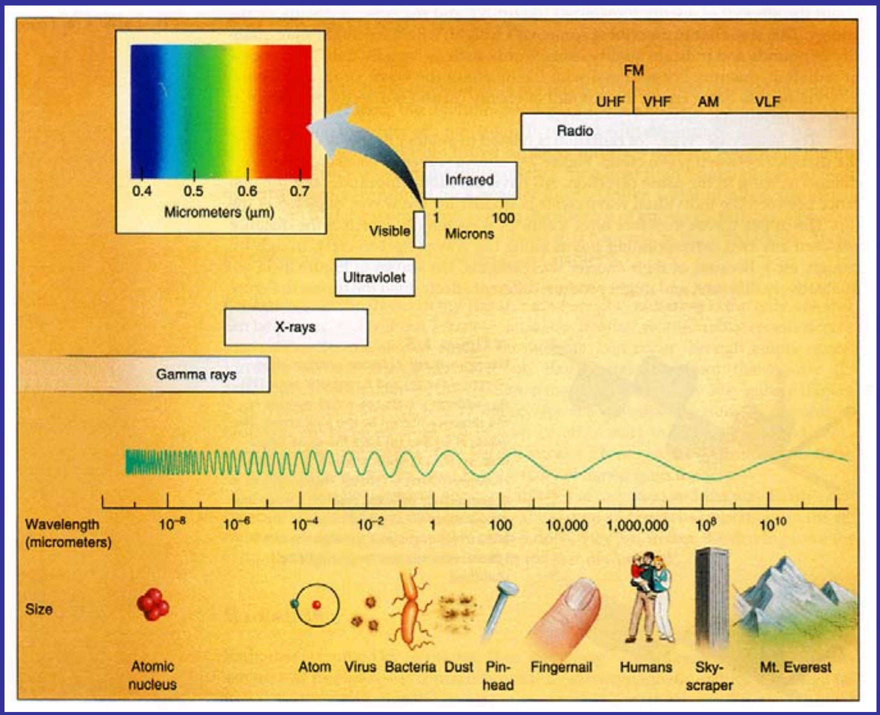


Table 2–1 Wavelength Categorizations

Type of Energy	Wavelength (micrometers)
Gamma	<0.0001
X ray	0.0001 to 0.01
Ultraviolet	0.01 to 0.4
Visible	0.4 to 0.7
Near Infrared (NIR)	0.7 to 4.0
Thermal Infrared	4 to 100
Microwave	100 to 1,000,000 (1 meter)
Radio	>1,000,000 (1 meter)

(from *Understanding Weather & Climate*)

- ❑ Radiation energy comes in an infinite number of wavelengths.
- ❑ We can divide these wavelengths into a few bands.

Wien's Law

$$\lambda_{max} = w/T$$

λ_{max} = wavelength (micrometers)

W = 2897 μm K

T = temperate (K)

- Wien's law relates an objective's maximum emitted wavelength of radiation to the objective's temperature.
- It states that the wavelength of the maximum emitted radiation by an object is inversely proportional to the objective's absolute temperature.

Apply Wien's Law To Sun and Earth

- **Sun**

  λ_{max} = 2898 μm K / 6000K

  = 0.483 μm

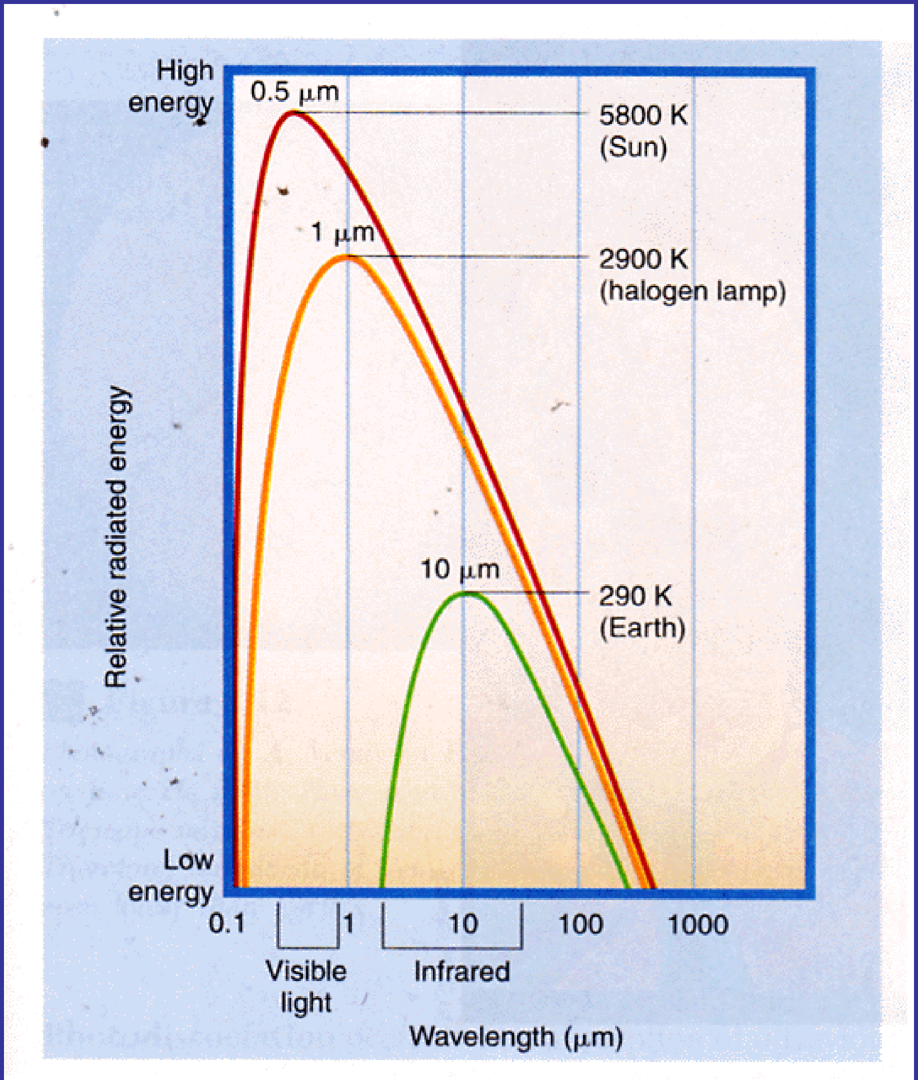
- **Earth**

  λ_{max} = 2898 μm K / 300K

  = 9.66 μm

- Sun radiates its maximum energy within the visible portion of the radiation spectrum, while Earth radiates its maximum energy in the infrared portion of the spectrum.

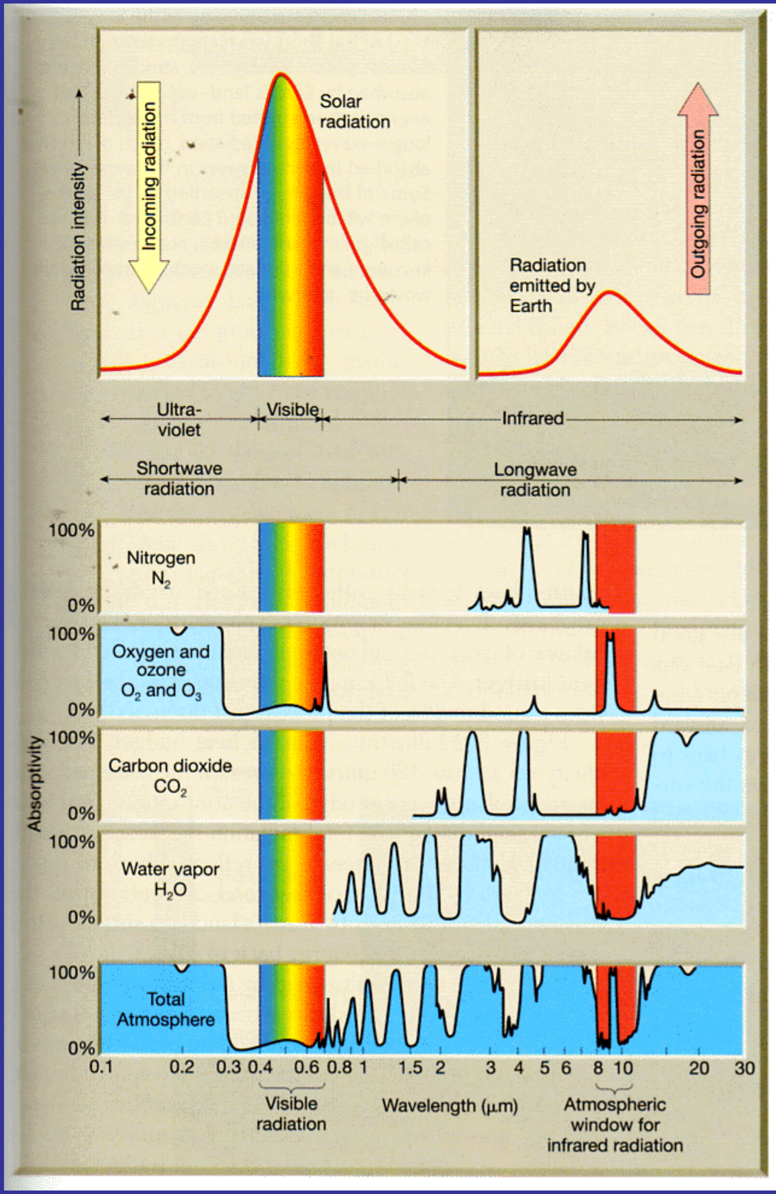
Wavelength and Temperature



(from *Meteorology: Understanding the Atmosphere*)

- The hotter the objective, the shorter the wavelength of the peak radiation.

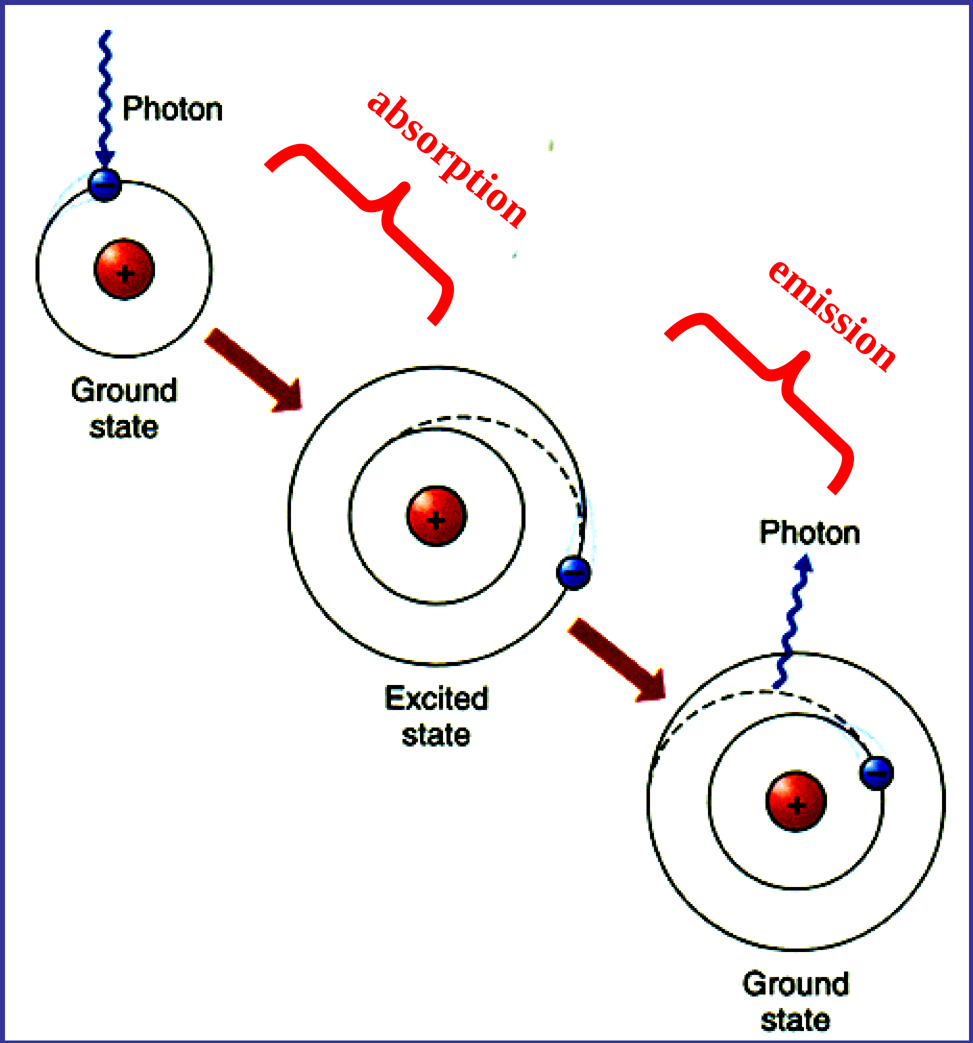
Selective Absorption and Emission



- 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*)

Why Selective Absorption/Emission?

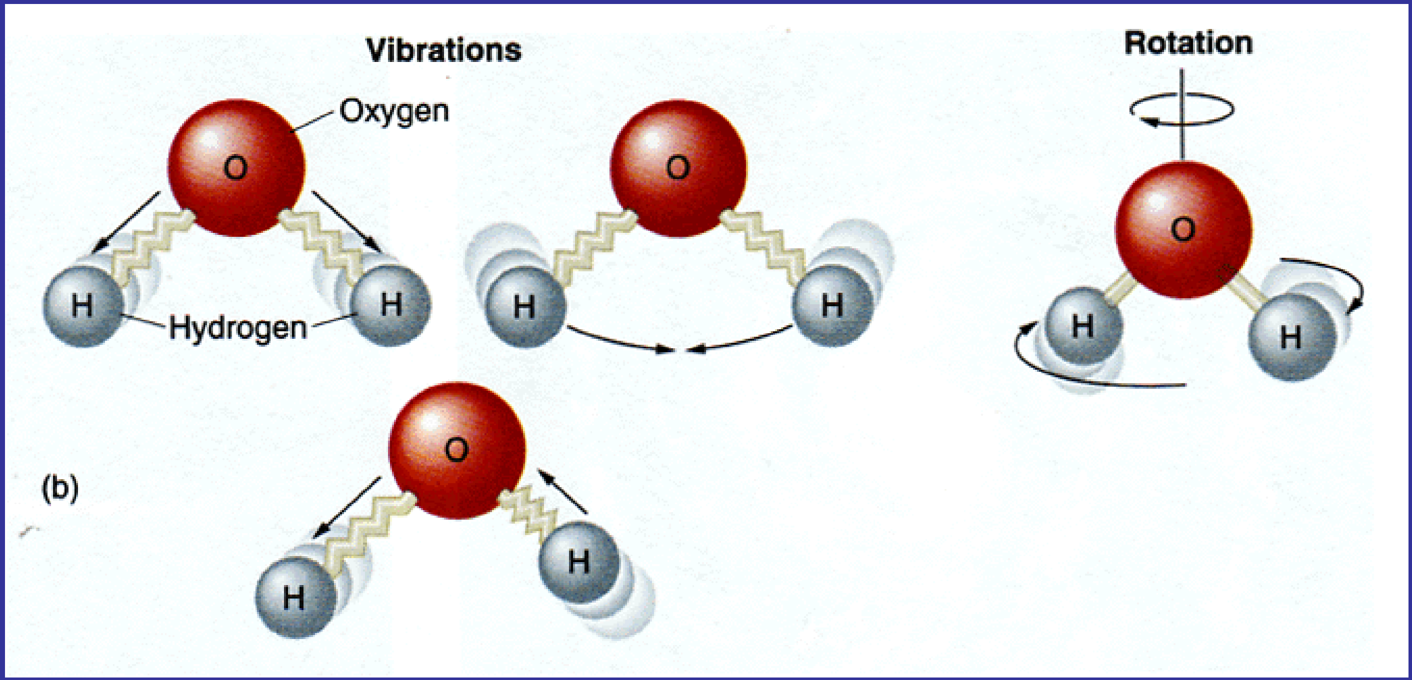


(from *Understanding Weather & Climate*)

- Radiation energy is absorbed or emitted to change the energy levels of atoms or molecular.
- The energy levels of atoms and molecular are discrete but not continuous.
- Therefore, atoms and molecular can absorb or emit certain amounts of energy that correspond to the differences between the differences of their energy levels.

➔ Absorb or emit at selective frequencies.

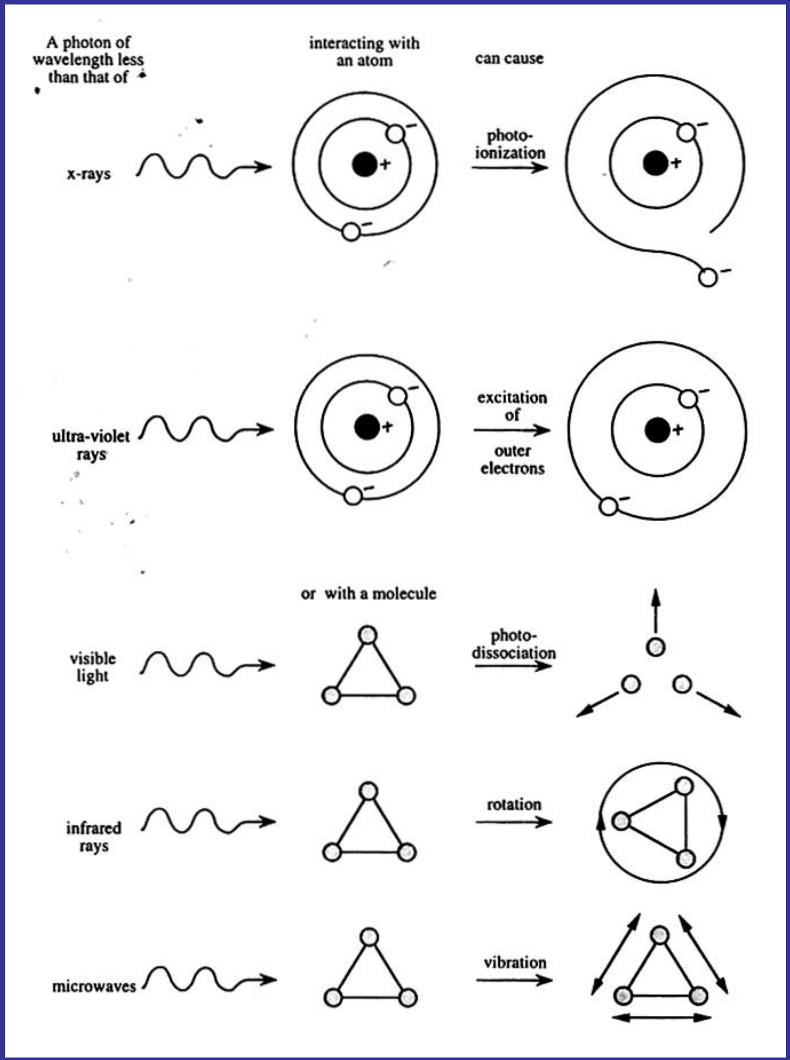
Different Forms of Energy Levels



(from *Understanding Weather & Climate*)

- The energy of a molecule can be stored in (1) translational (the gross movement of molecules or atoms through space), (2) vibrational, (3) rotational, and (4) electronic (energy related to the orbit) forms.

Energy Required to Change the Levels



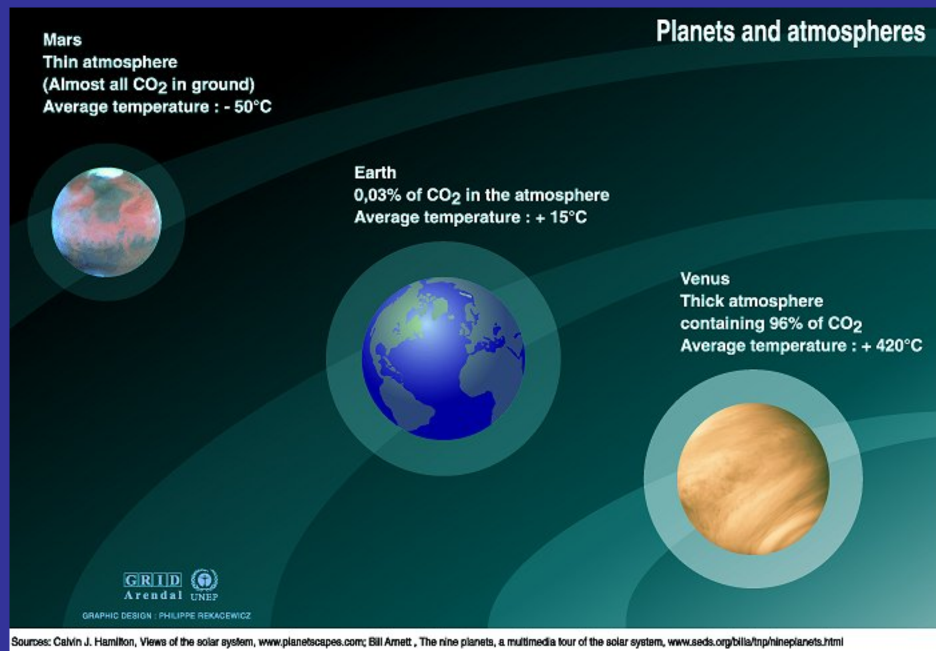
- The most energetic photons (with shortest wavelength) are at the top of the figure, toward the bottom, energy level decreases, and wavelengths increase.

(from *Is The Temperature Rising?*)

Three Factors To Determine Planet Temperature

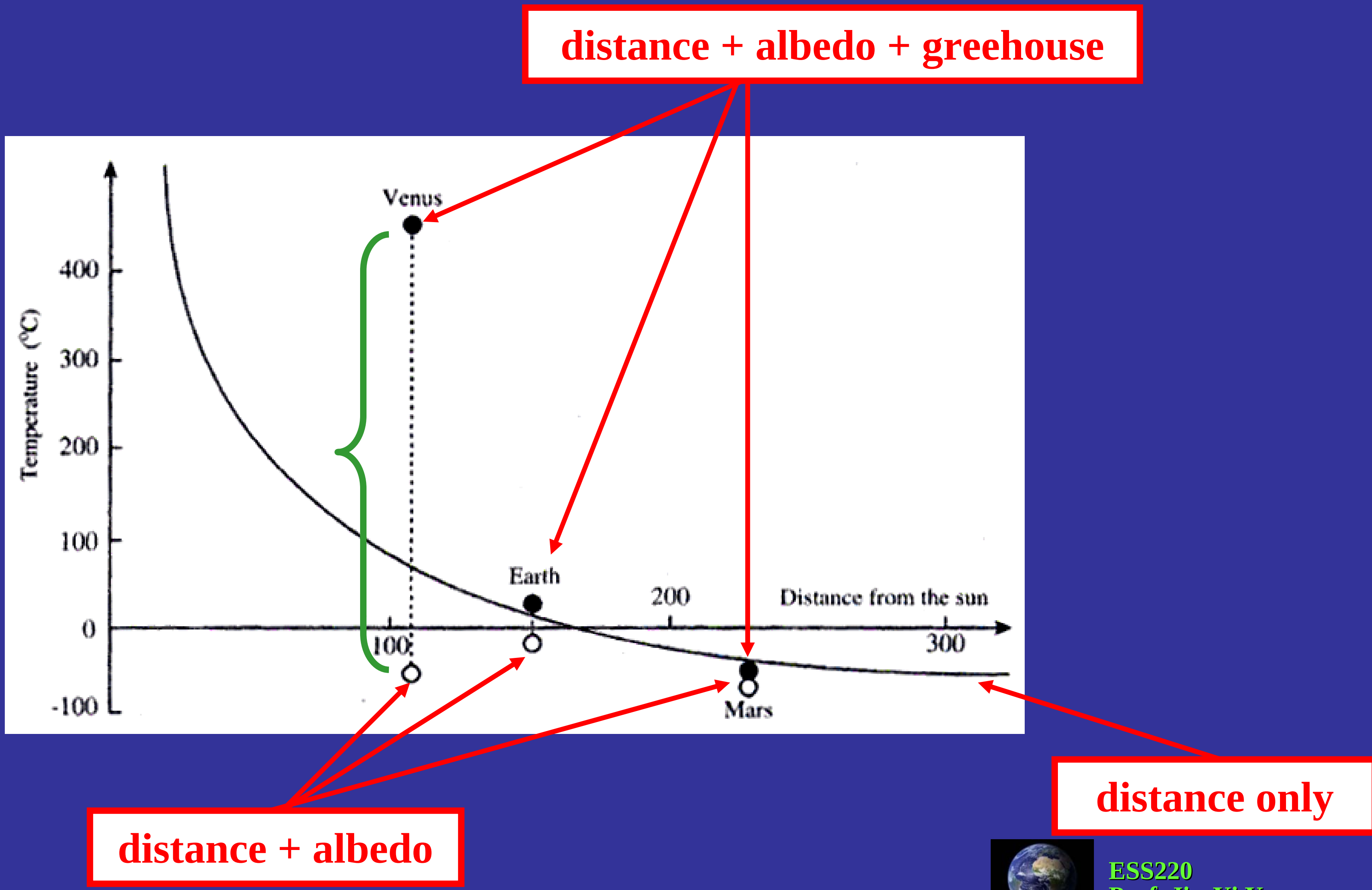
- Distance from the Sun
- Albedo
- Greenhouse effect

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



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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

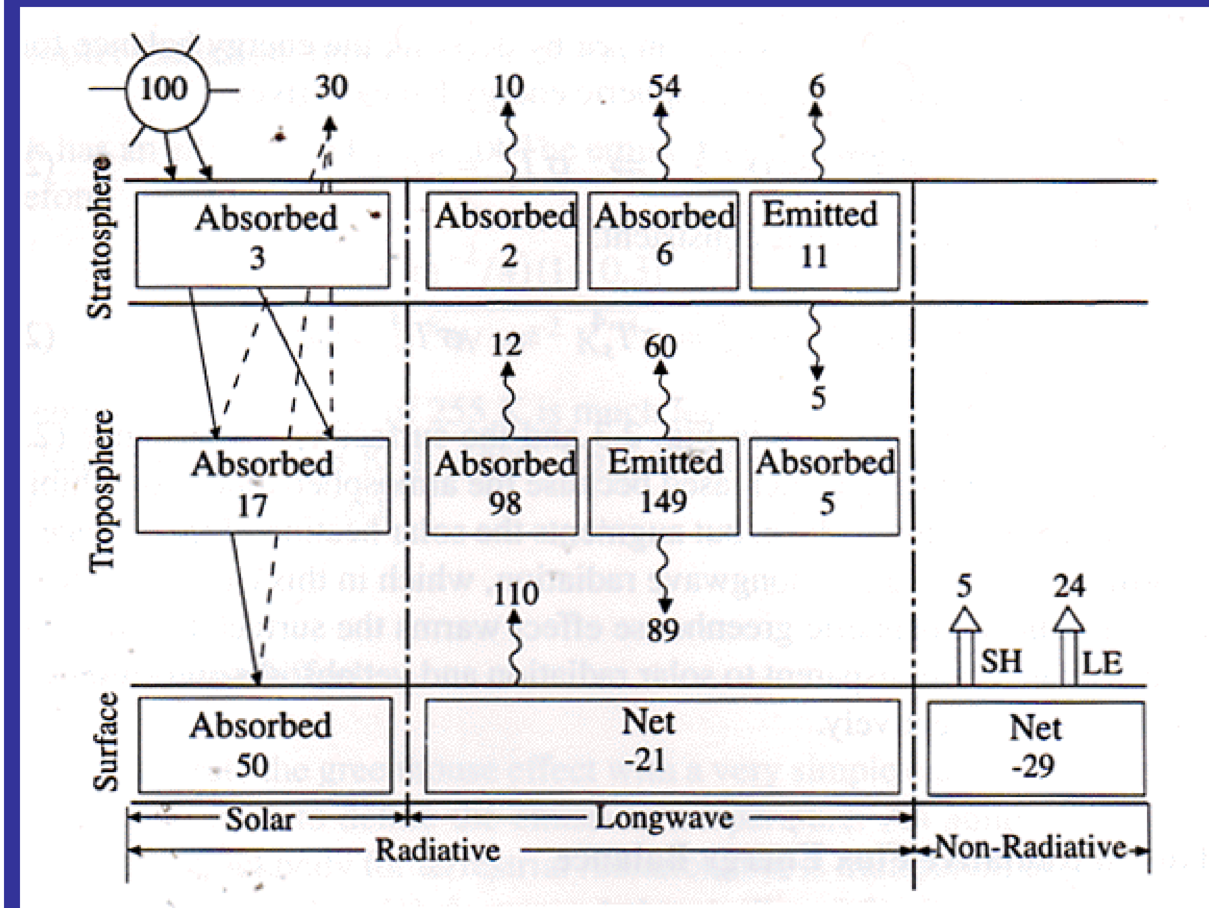
→ Carbon can not be injected back to the atmosphere

→ 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

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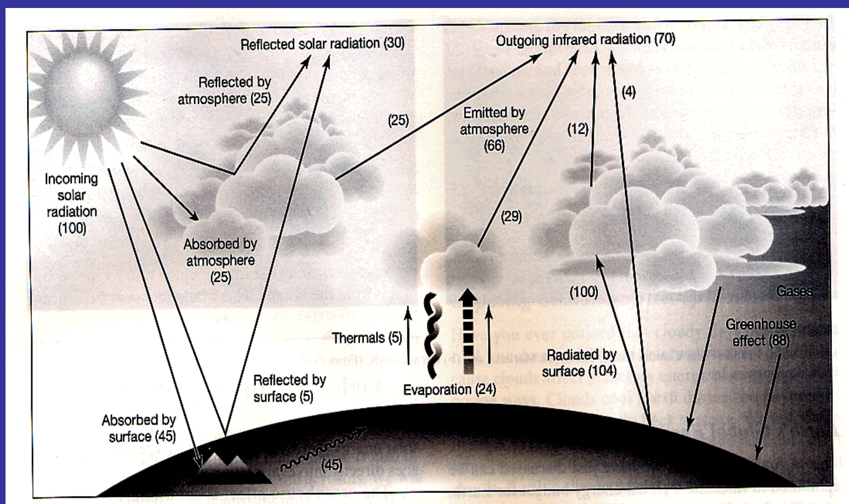
Where Is Earth's Radiation Emitted From?



(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 Type Based On Properties

❑ Four basic cloud categories:

✓ Cirrus --- thin, wispy cloud of ice.

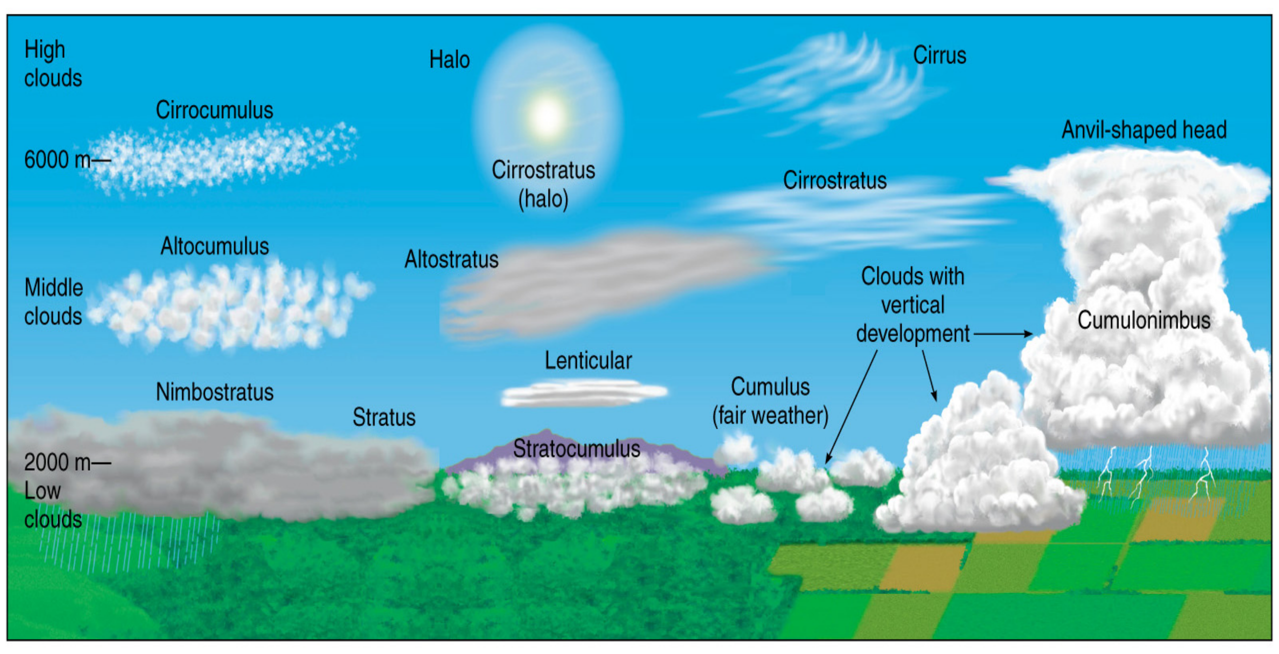
✓ Stratus --- layered cloud

✓ 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.

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*")

Important Roles of Clouds In Global Climate

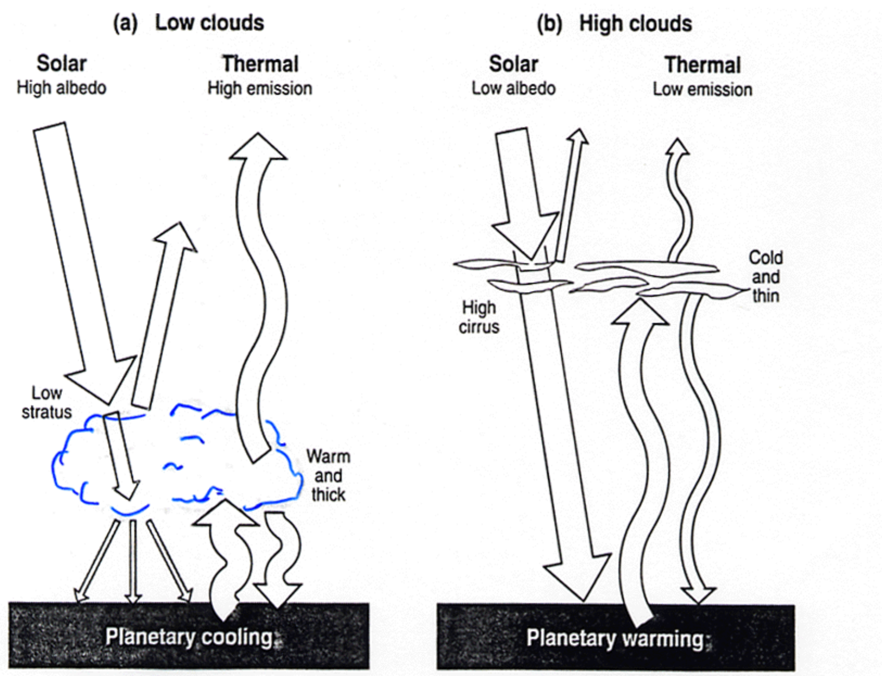
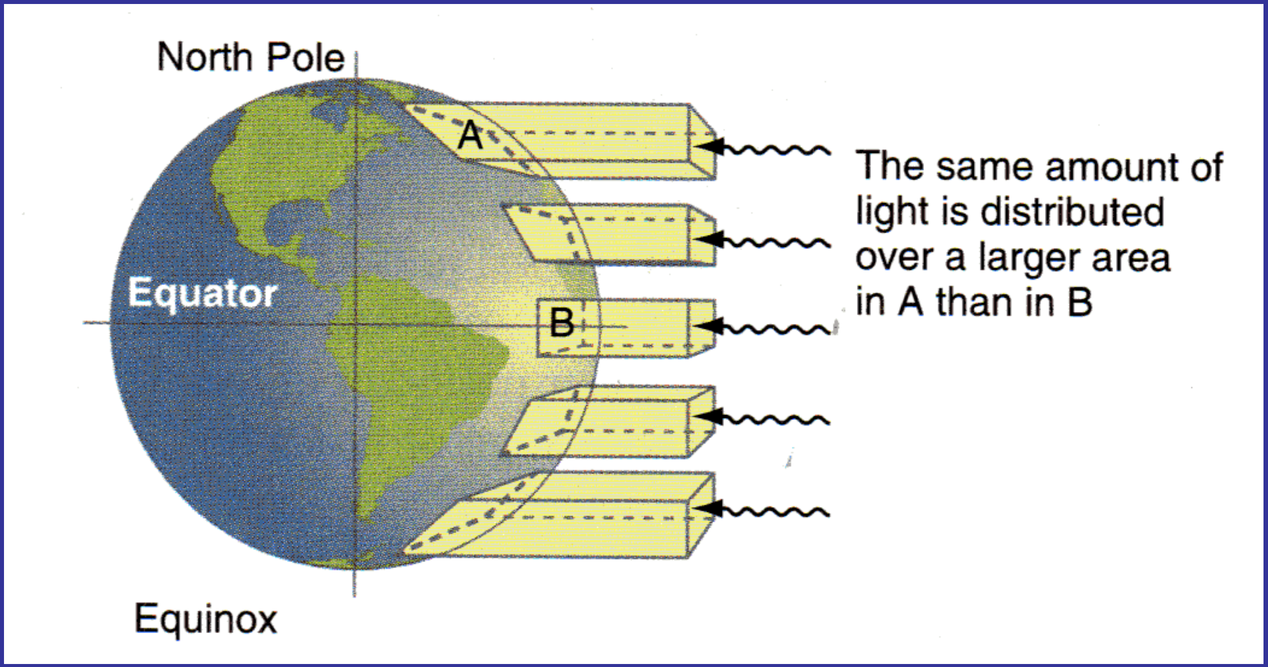


Figure 11.13 The effects of clouds on the flow of radiation and energy in the lower atmosphere and at the surface. Two cases are shown: (a) low clouds, with a high solar albedo and high thermal emission temperature; and (b) high clouds, with a low solar albedo and low thermal emission temperature. The 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

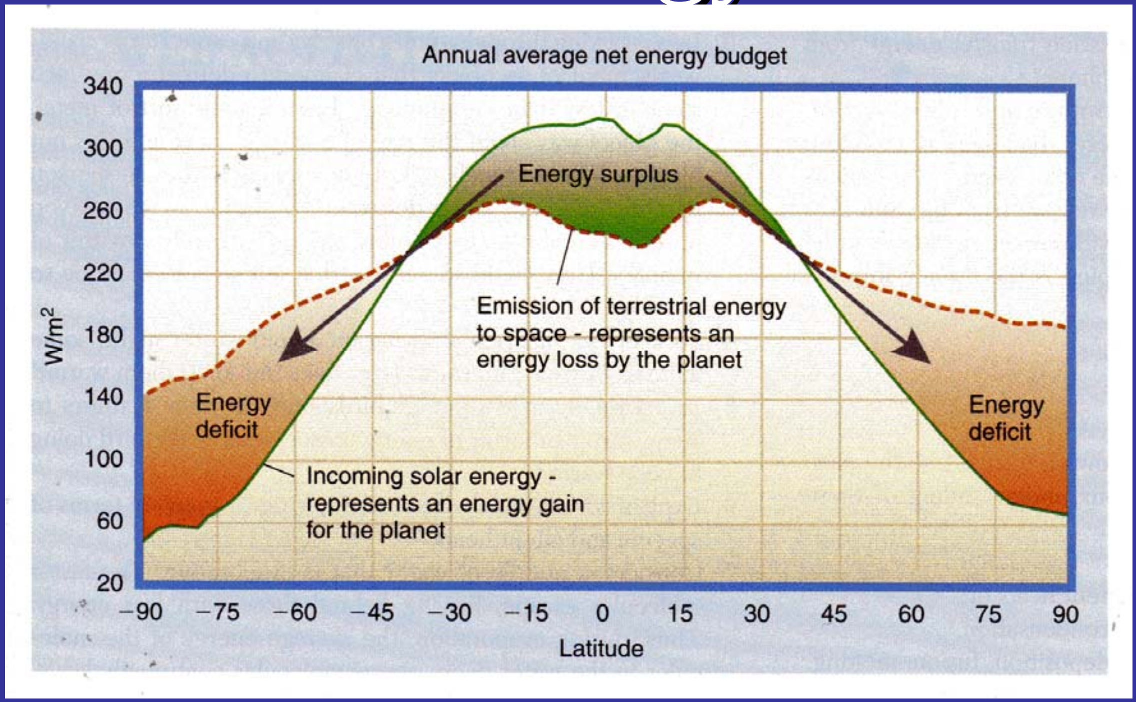
Zenith Angle and Insolation



(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

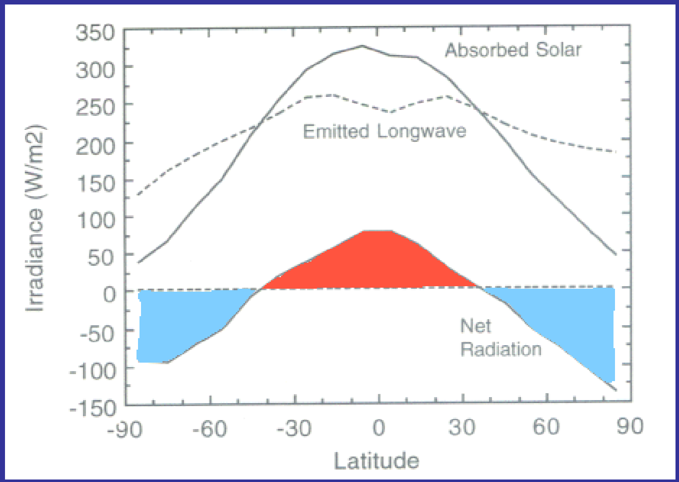


(from *Meteorology: Understanding the Atmosphere*)

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

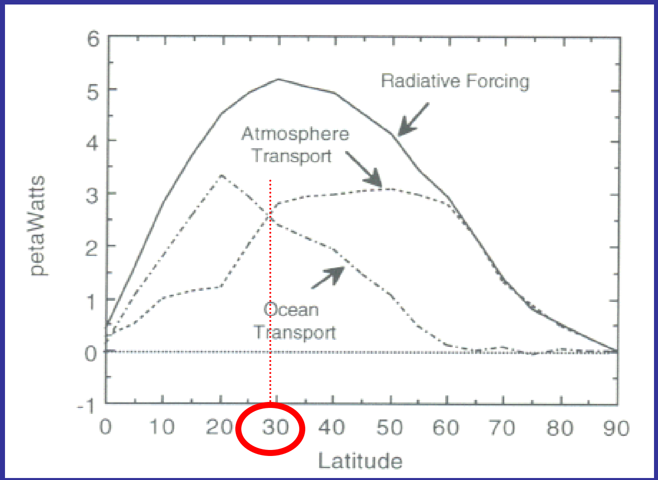
Polarward Energy Transport

Annual-Mean Radiative Energy



Polarward heat flux 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*)

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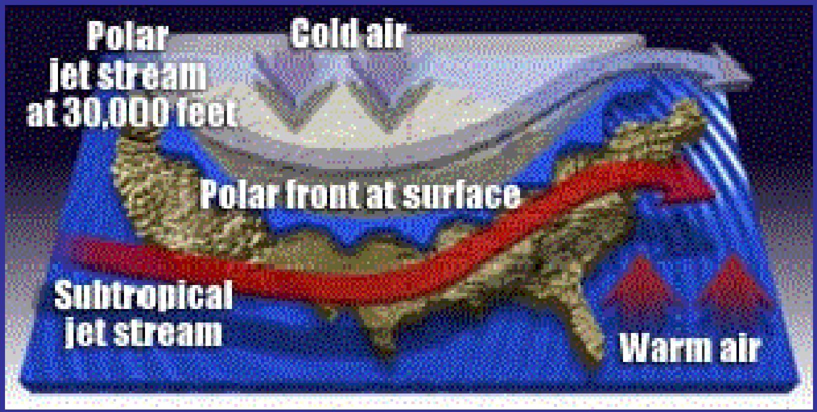
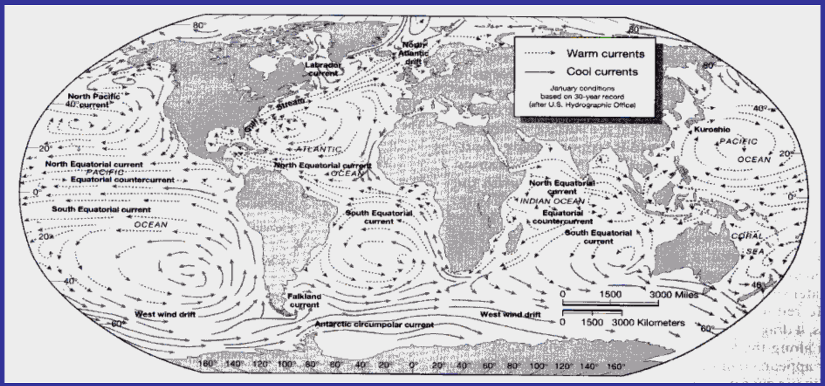
How Do Atmosphere and Ocean Transport Heat?

Atmospheric Circulation



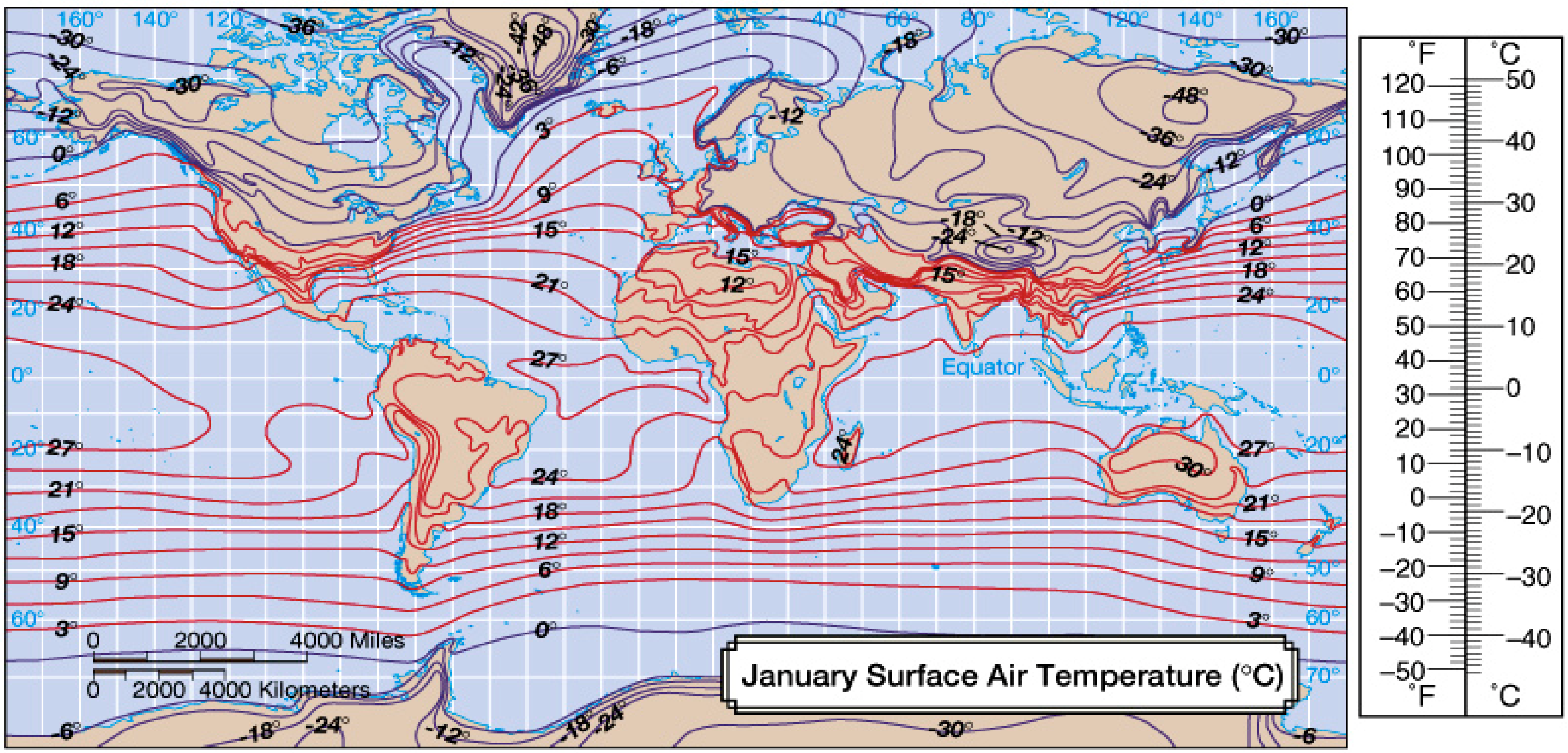
(from USA Today)

Ocean Circulation



(from *The Earth System*)

Isotherm



January Surface Air Temperature (°C)
Equator
0 2000 4000 Miles
0 2000 4000 Kilometers
°F
°C
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
−30
−40
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50
40
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