Chapter 3: Energy Balance and Temperature

- Planet Energy Balance
- Greenhouse Effect
- Selective Absorption of Atmosphere
- Absorption, Reflection, Transmission
- Temperature Distribution

Planetary Energy Balance

Solar Energy Absorbed = Terrestrial Energy Emitted

⇓

Determine Planet's Surface Temperature

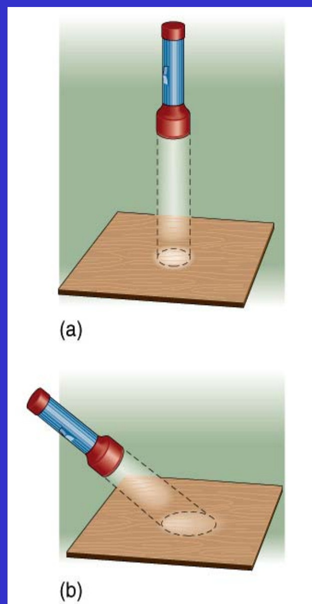
Solar Flux Density Reaching Earth

- Solar Constant (*S*)

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

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

Solar Energy Incident On the Earth



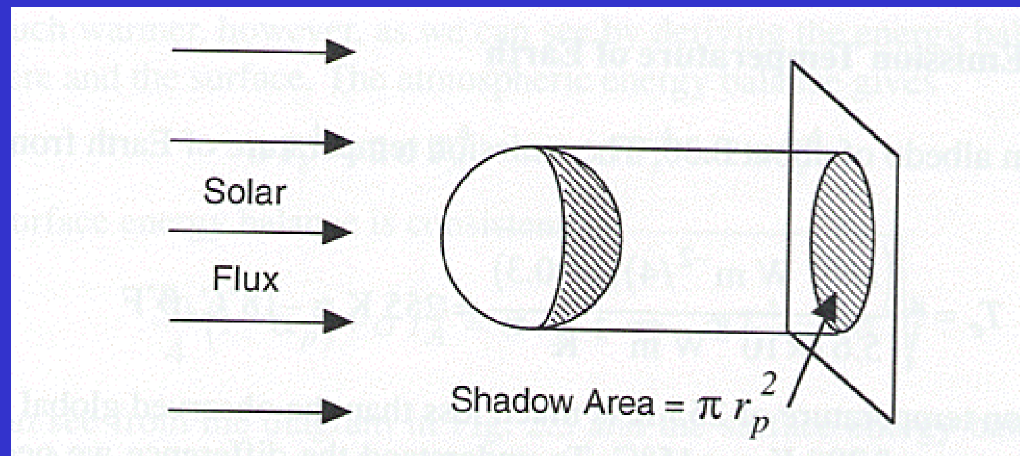
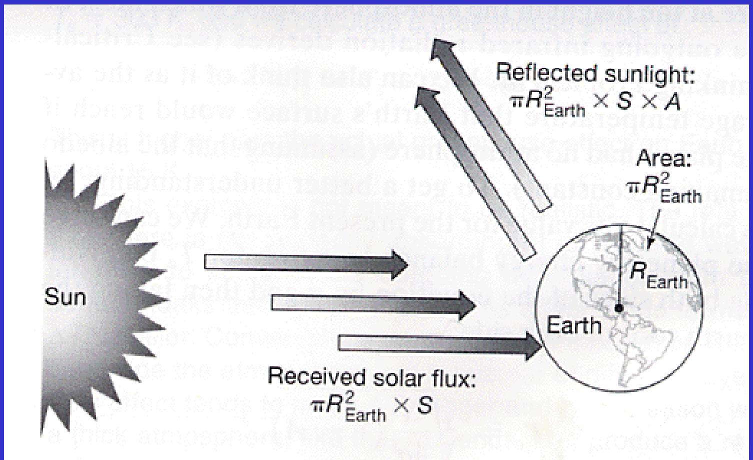


Fig. 2.2 Diagram showing the shadow area of a spherical planet.

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

Solar Energy Absorbed by Earth



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

(from *The Earth System*)

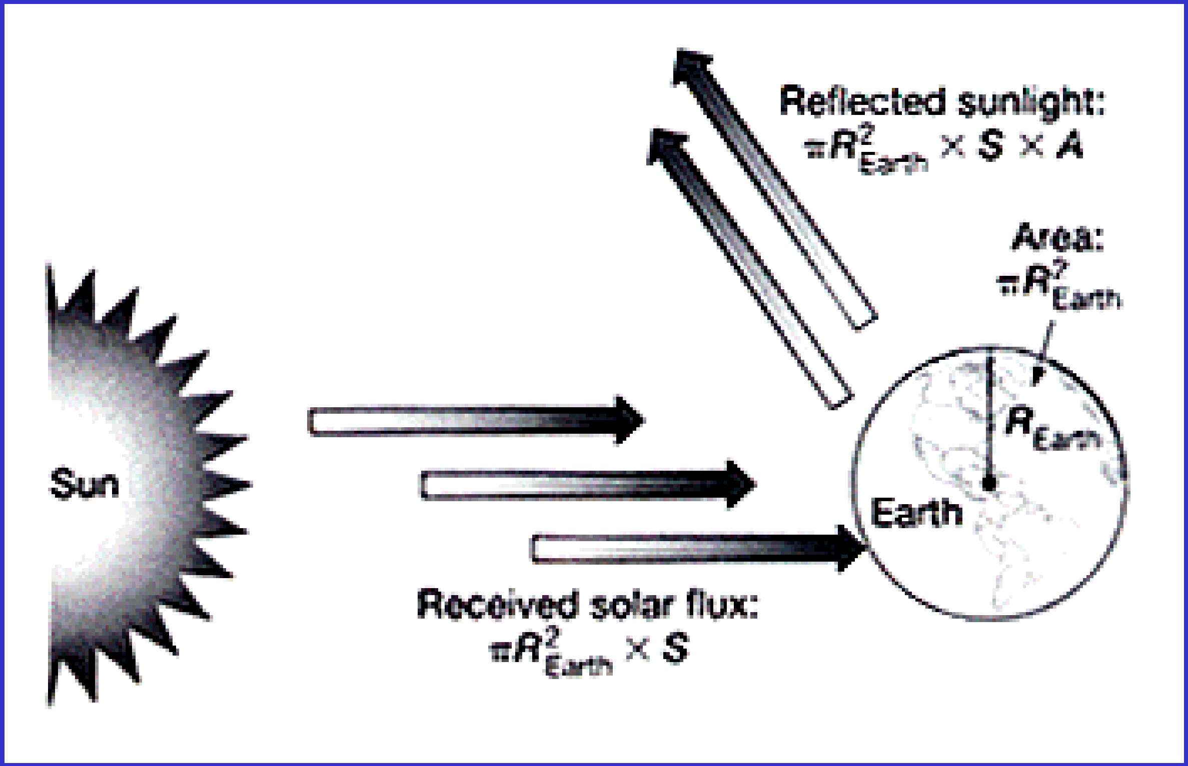
- **Solar Constant (S)**
  = solar flux density reaching the Earth
  = 1370 W/m^2

- **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.

Albedo and Surface Type

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).*

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.

Energy Emitted from Earth

- **The Stefan-Boltzmann Law**

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

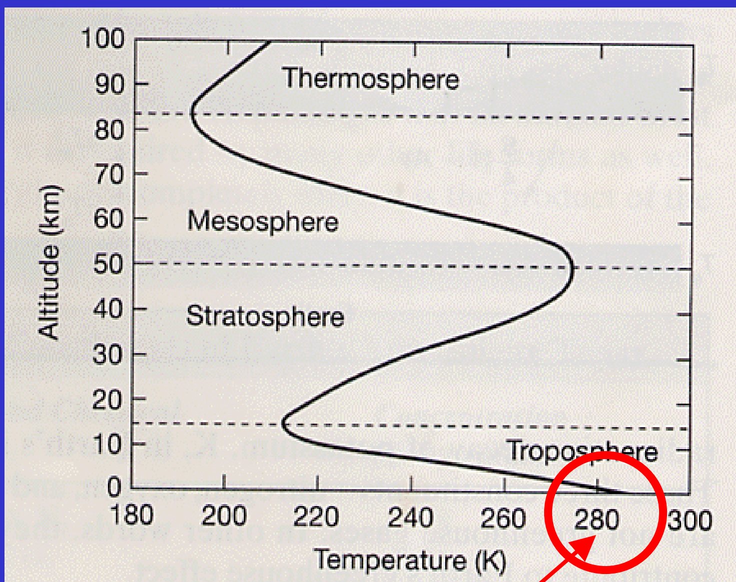
  $\mathbf{F = \sigma T^4}$ where σ is 5.67×10^{-8} W/m^2/K

- **Energy emitted from the Earth**

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

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

Planetary Energy Balance



(from *Global Physical Climatology*)

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

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

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

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

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

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

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

T_e = 255 K (-18°C)

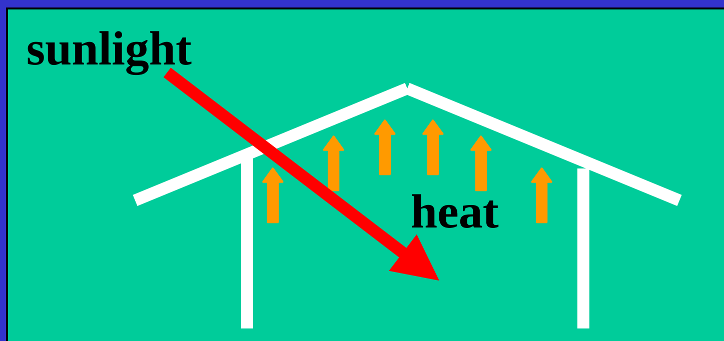
Earth's *surface* temperature

T_S = 288 K (15 °C)

greenhouse effect (33C) !!

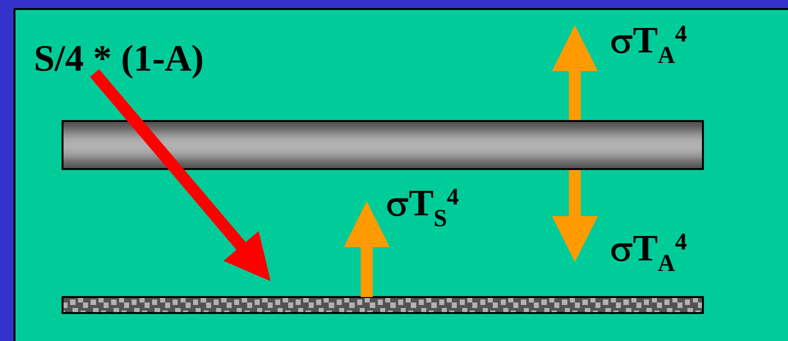
Greenhouse Effect

Greenhouse



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

Atmosphere



- For Earth's surface:

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

- For the atmosphere:

  $\sigma T_S^4 = 2\sigma T_A^4$

➔ $T_s = 2^{1/4}\, T_A$ = 303K

Greenhouse Gases

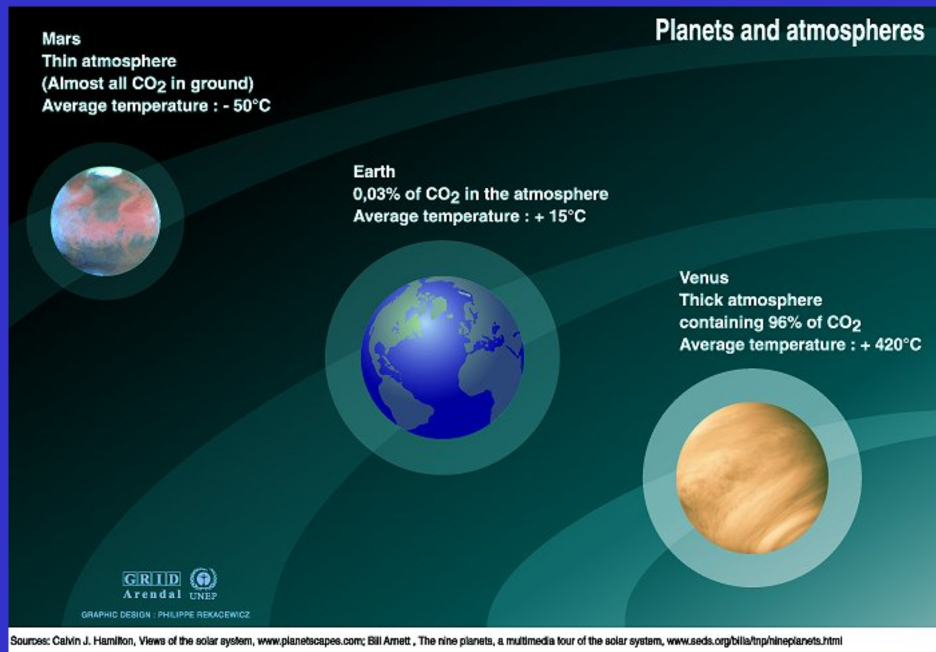
Important Atmospheric Greenhouse Gases

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

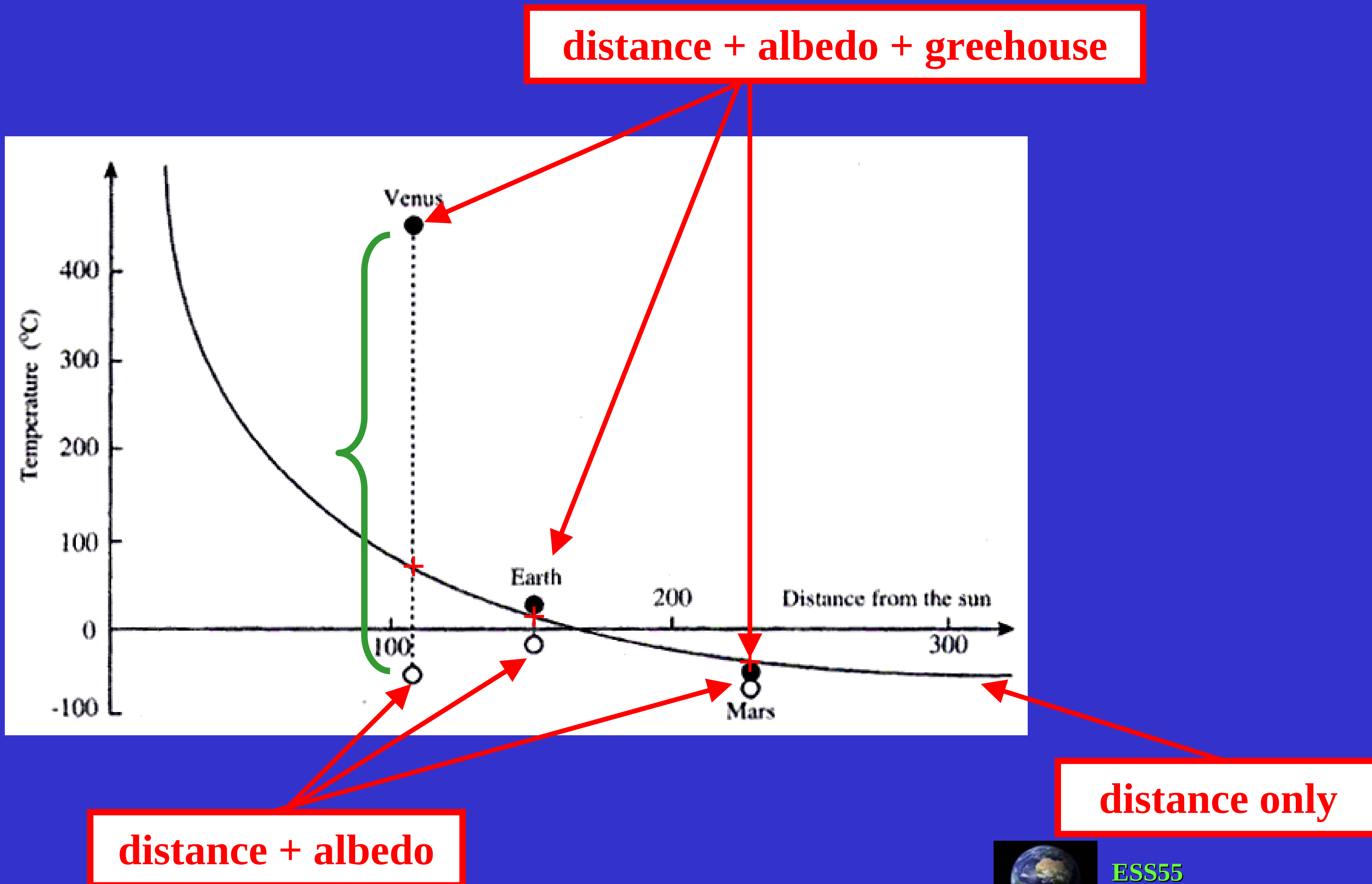
- Distance from the Sun
- Albedo
- Greenhouse effect

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

Global Temperature



ESS55
Prof. Jin-Yi Yu

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

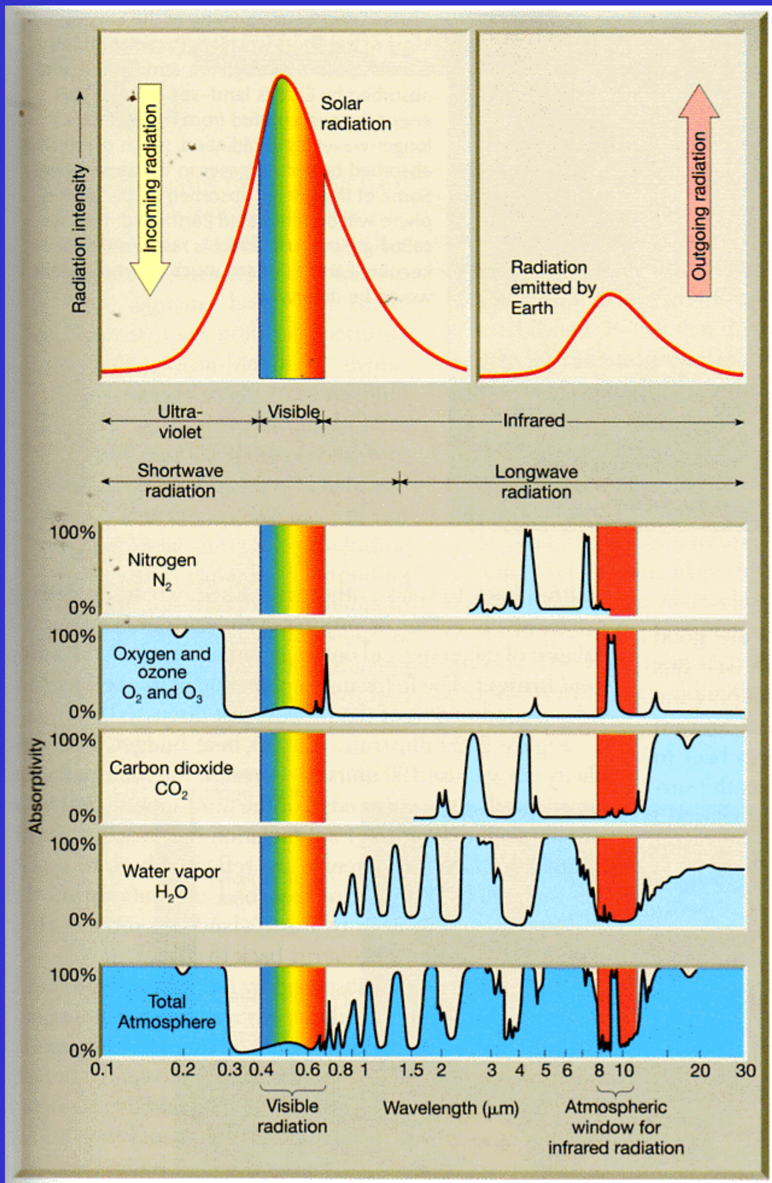
→ No tectonic activity on Mars

→ Carbon can not be injected back to the atmosphere

→ Little greenhouse effect

→ **A very cold Mars!!**

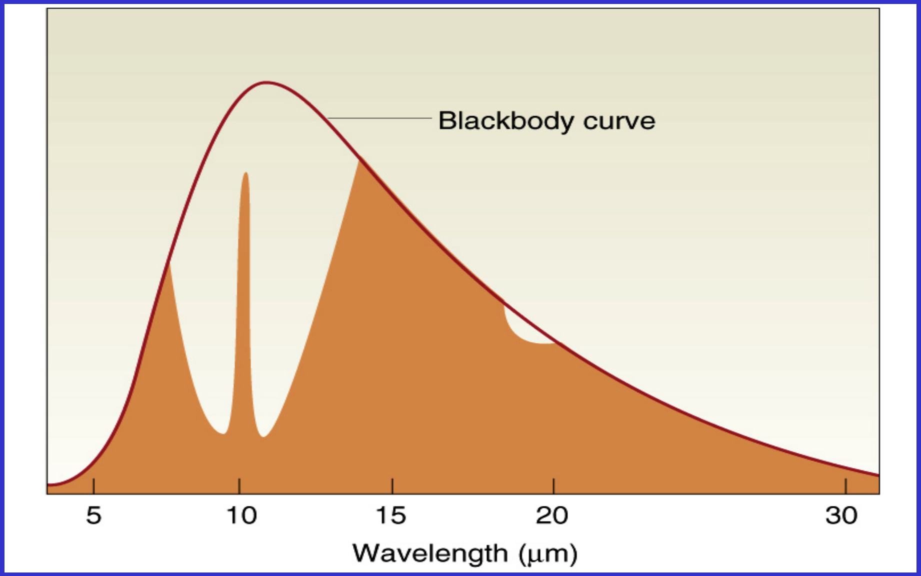
Selective Absorption and Emission



- 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.

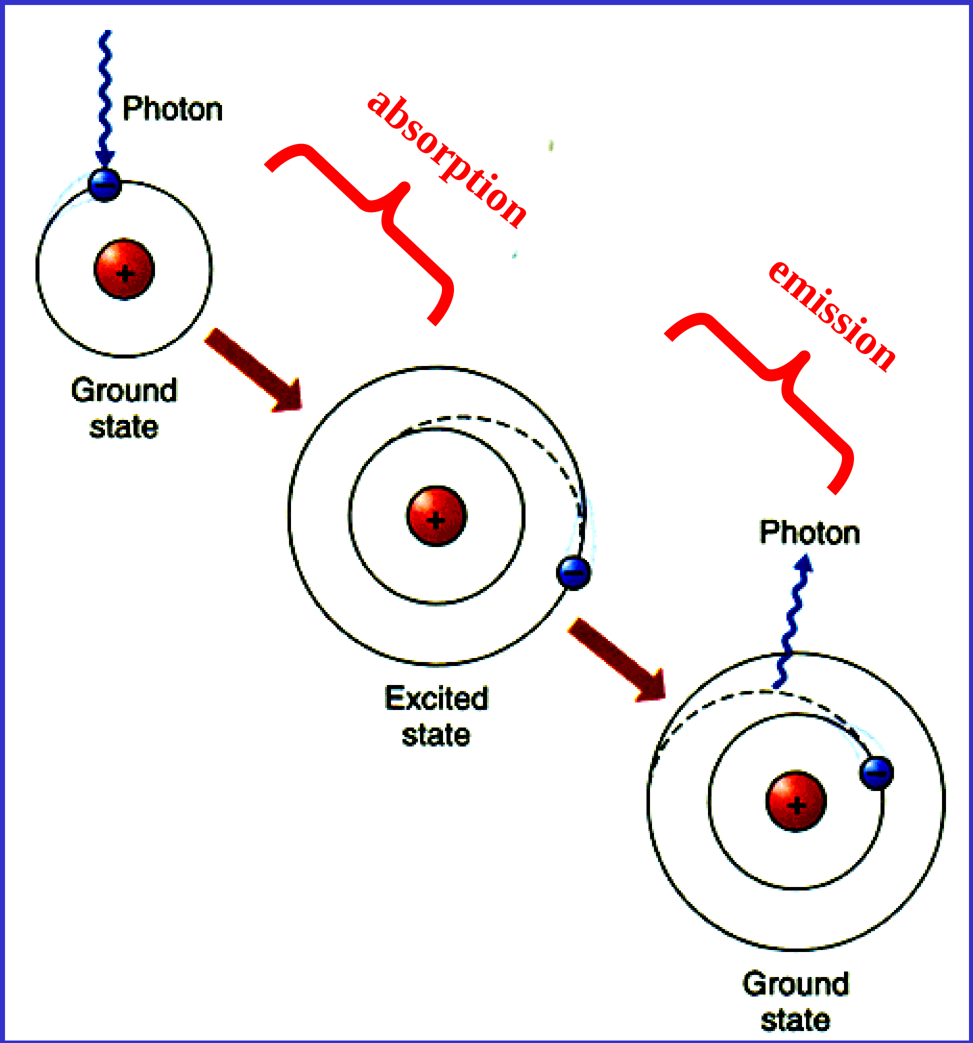
(from *The Atmosphere*)

Atmospheric Window for Terrestrial Radiation



- A portion of the longwave spectrum can pass through the atmosphere unimpeded.
- This range of wavelengths, 8-15μm, match those radiated with greatest intensity by the Earth's surface.
- This range of wavelengths not absorbed is called the ***atmospheric window.***

Why Selective Absorption/Emission?

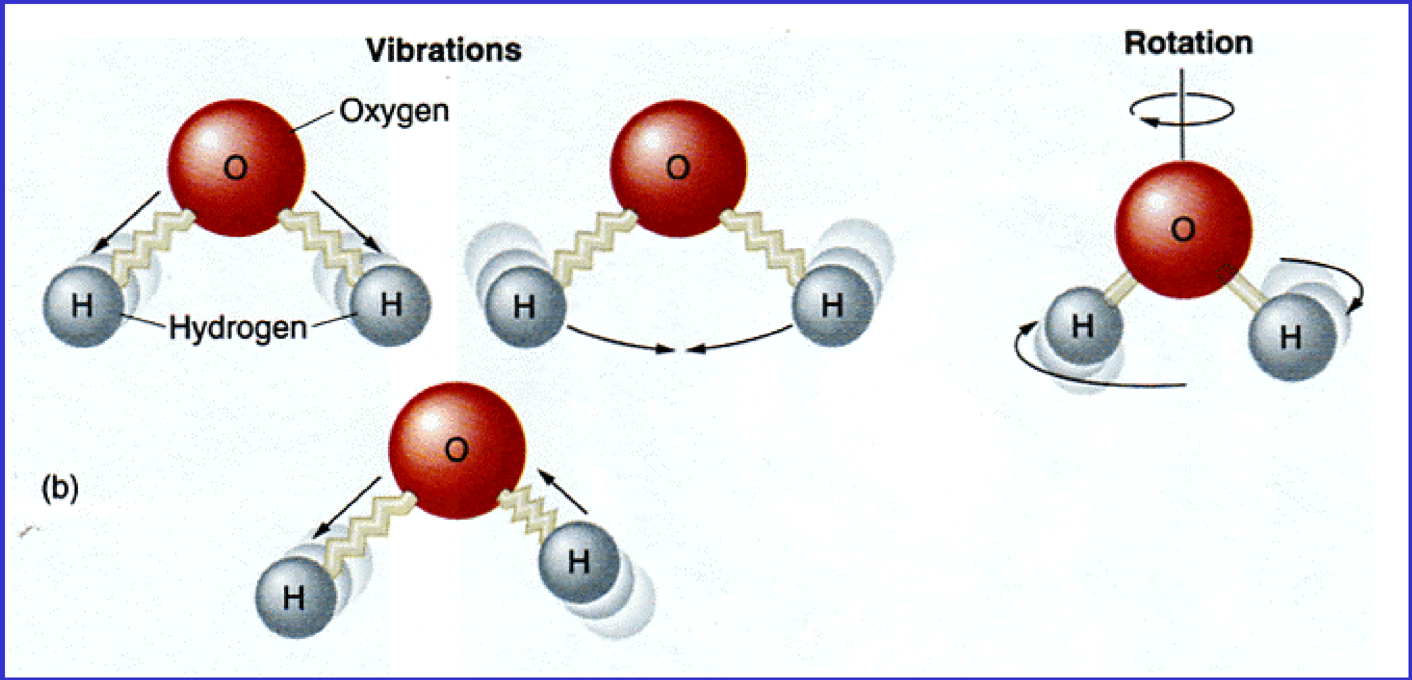


(from *Understanding Weather & Climate*)

- ❑ 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.

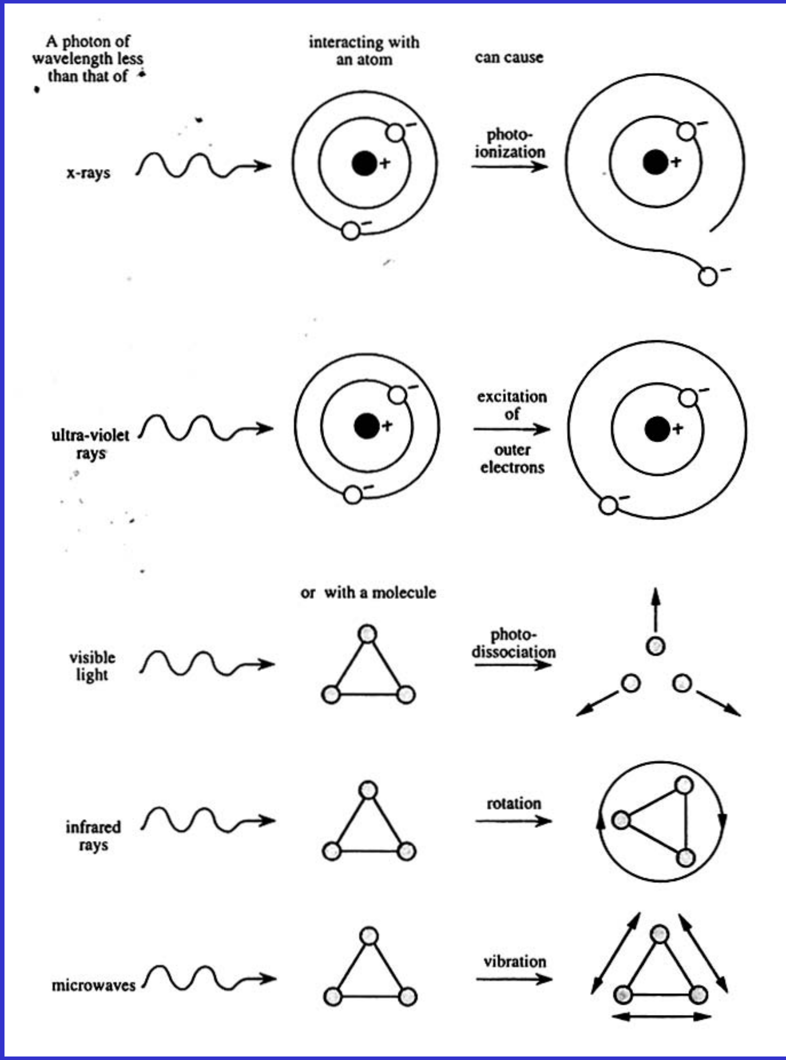
Different Forms of Energy Levels



(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



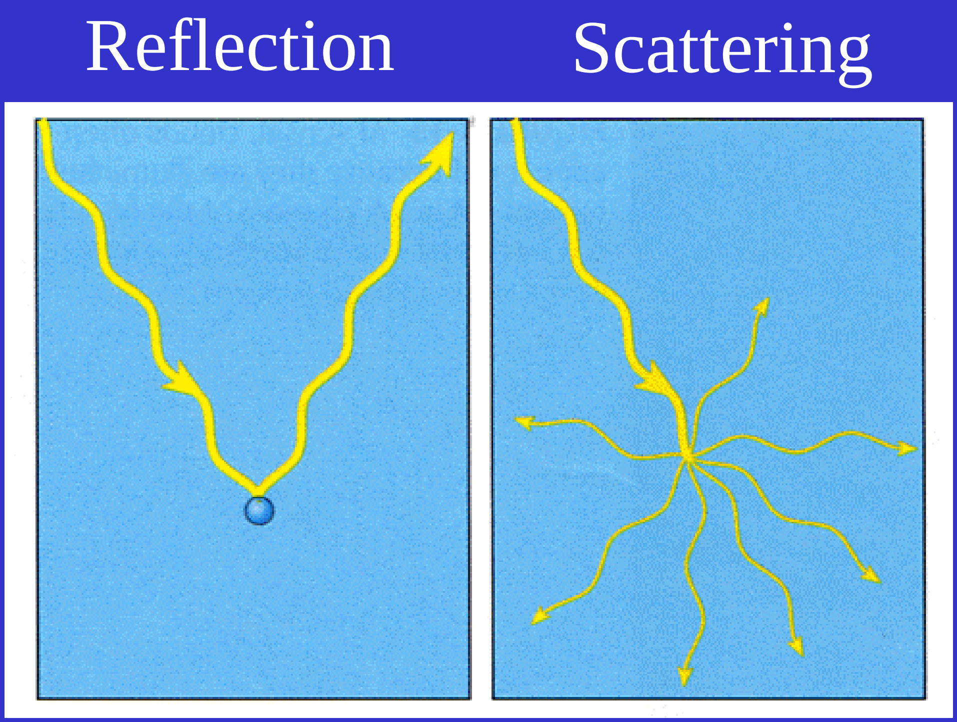
- The most energetic photons (with shortest wavelength) are at the top of the figure, toward the bottom, energy level decreases, and wavelengths increase.

(from *Is The Temperature Rising?*)

Atmospheric Influences on Insolation

- Absorption
  - convert insolation to heat the atmosphere
- Reflection / Scattering
  - change the direction and intensity of insolation
- Transmission
  - no change on the direction and intensity of insolation

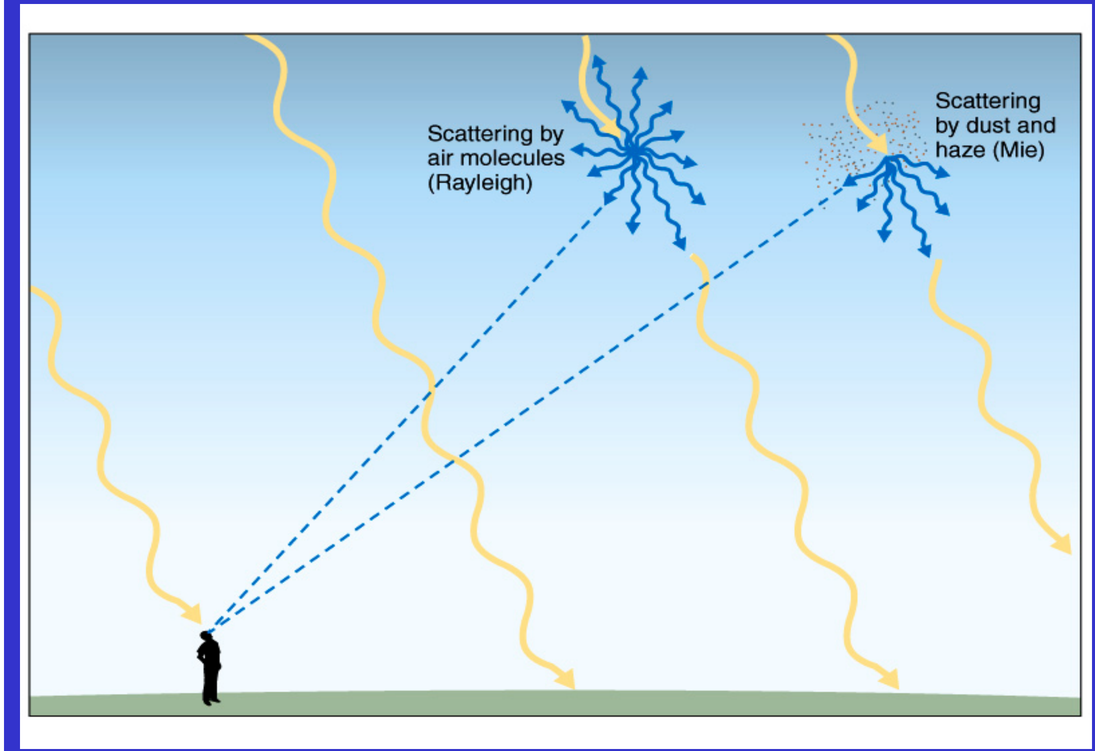
Reflection and Scattering



(from *The Atmosphere*)

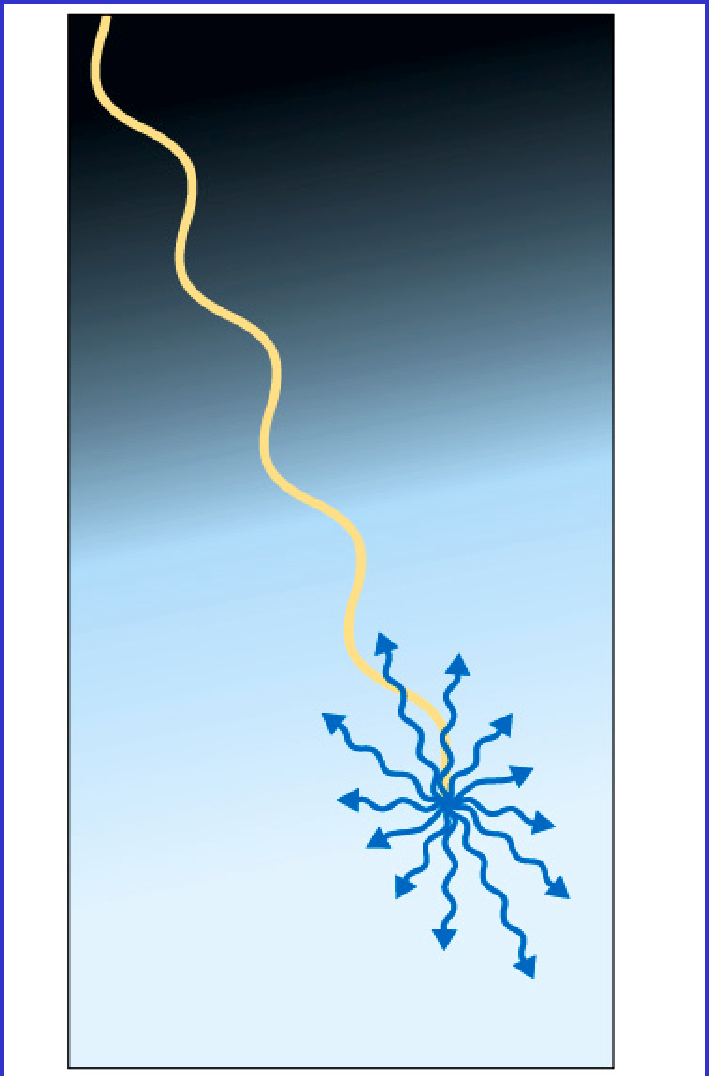
- Reflection: light bounces back from an objective at the same angle at which it encounters a surface and with the same intensity.
- Scattering: light is split into a larger number of rays, traveling in different directions.
- Although scattering disperses light both forward and backward (backscattering), more energy is dispersed in the forward direction.

Scattering



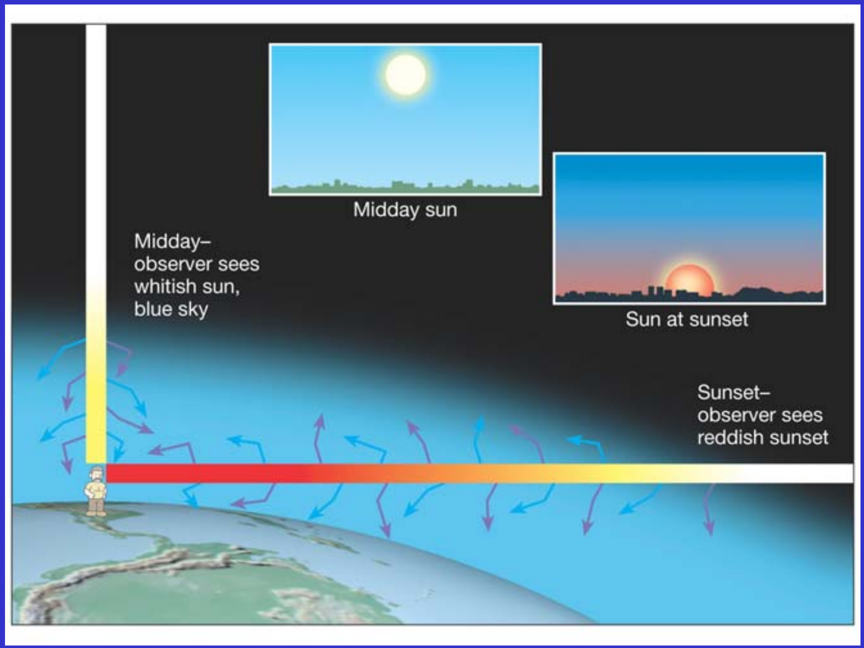
- ❑ Scattering is a process whereby a beam of radiation is broken down into many weaker rays redirected in other direction.
- ❑ Gases in the atmosphere effectively scatter radiation.
- ❑ Characteristics of scattering are dependent upon the size of the scattering agents: (1) Rayleigh Scattering, (2) Mie Scattering, (3) nonselective Scattering.

Rayleigh Scattering (Gas Molecules)



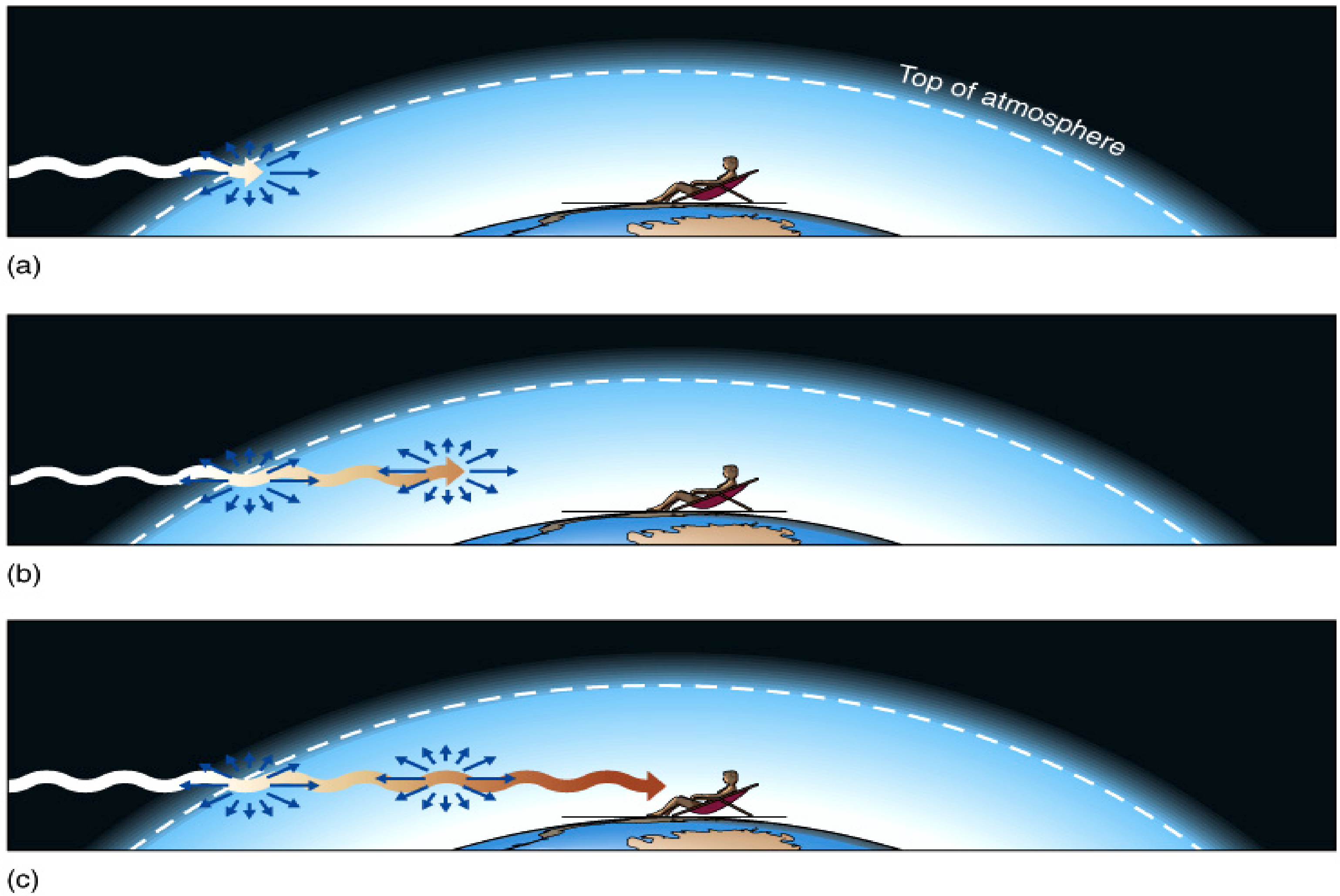
- Involves gases, or other scattering agents that are smaller than the energy wavelengths.
- Scatter energy forward and backward.
- Partial to shorter wavelength energy, such as those which inhabit the shorter portion of the visible spectrum.
- Responsible for (1) blue sky in clear days, (2) blue tint of the atmosphere when viewed from space, and the redness of sunsets and sunrises.

Scattering and Colors



- Short wavelengths (blue and violet) of visible light are scattered more effectively than are longer wavelengths (red, orange). Therefore, when the Sun is overhead, an observer can look in any direction and see predominantly blue light that was selectively scattered by the gases in the atmosphere.
- At sunset, the path of light must take through the atmosphere is much longer. Most of the blue light is scattered before it reaches an observer. Thus the Sun appears reddish in color.

Rayleigh Scattering Causes the redness of sunsets and sunrises



Spectrum of Radiation

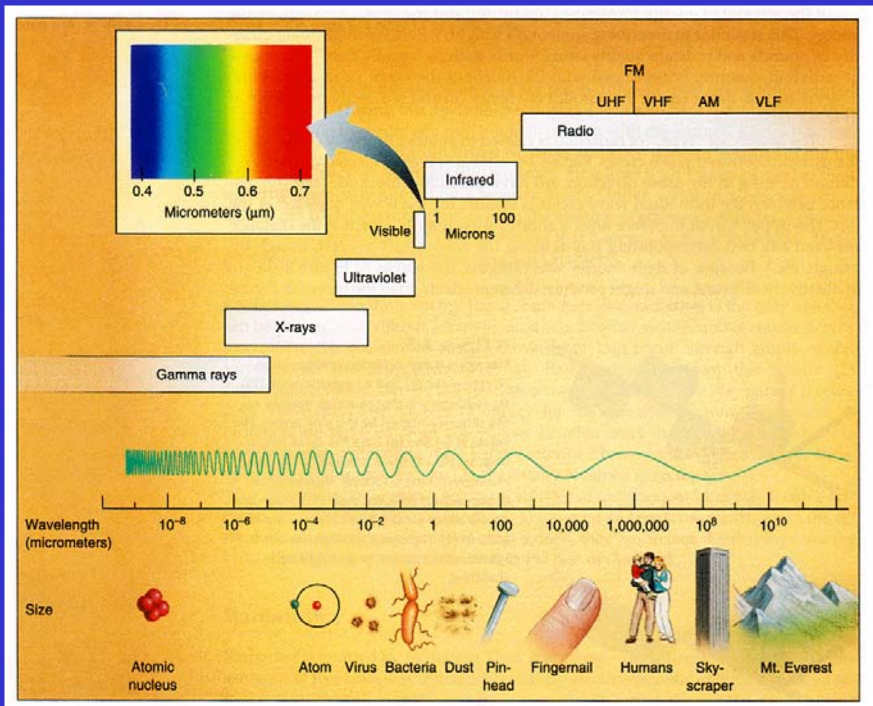


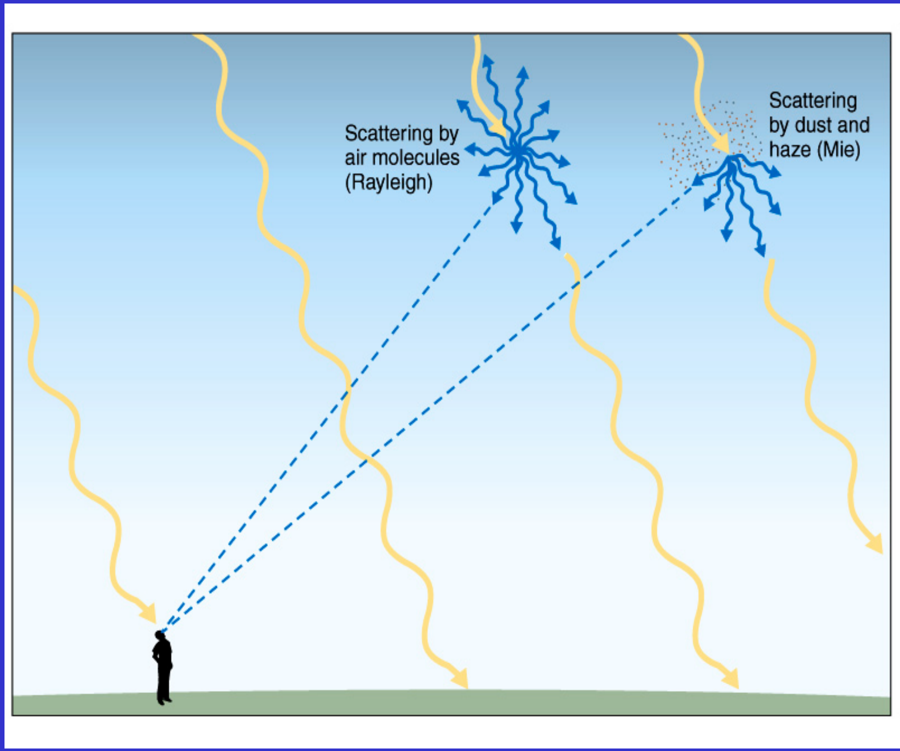
Table 2–1 Wavelength Categorizations

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.

Mie Scattering (Aerosols)

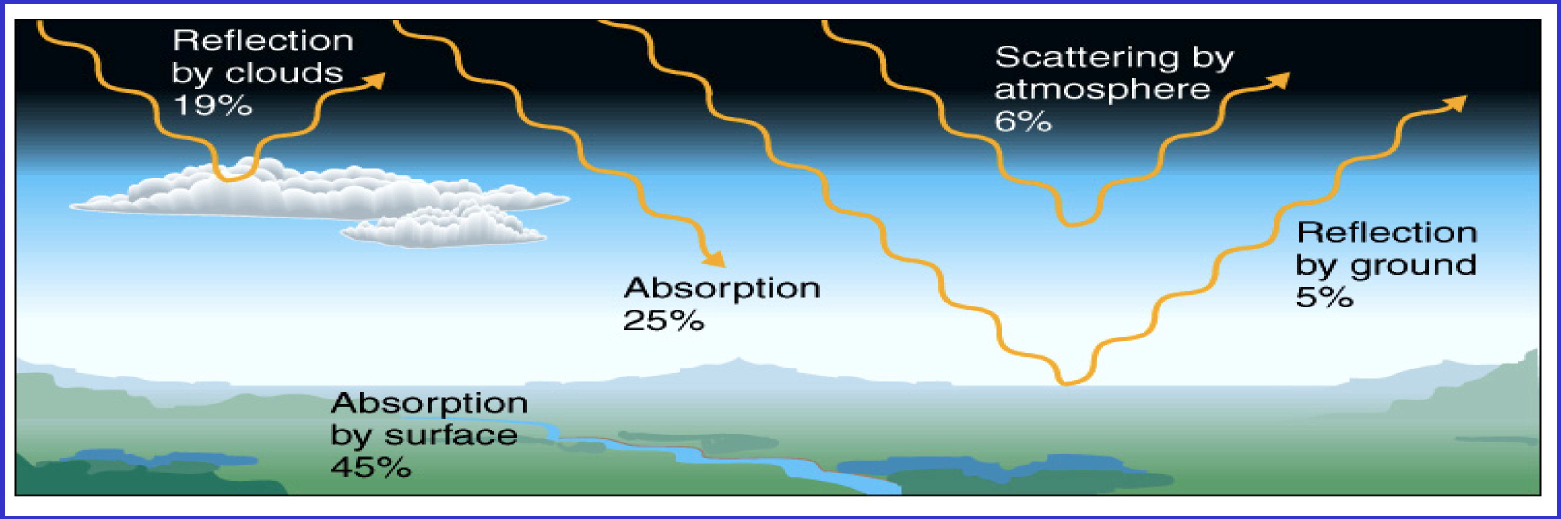


- Larger scattering agents, such as suspended aerosols, scatter energy only in a ***forward*** manner.
- Larger particles interact with wavelengths across the visible spectrum.
- Produces hazy or grayish skies.
- Enhances longer wavelengths during sunrises and sunsets, indicative of a rather aerosol laden atmosphere.

Nonselective Scattering (Clouds)

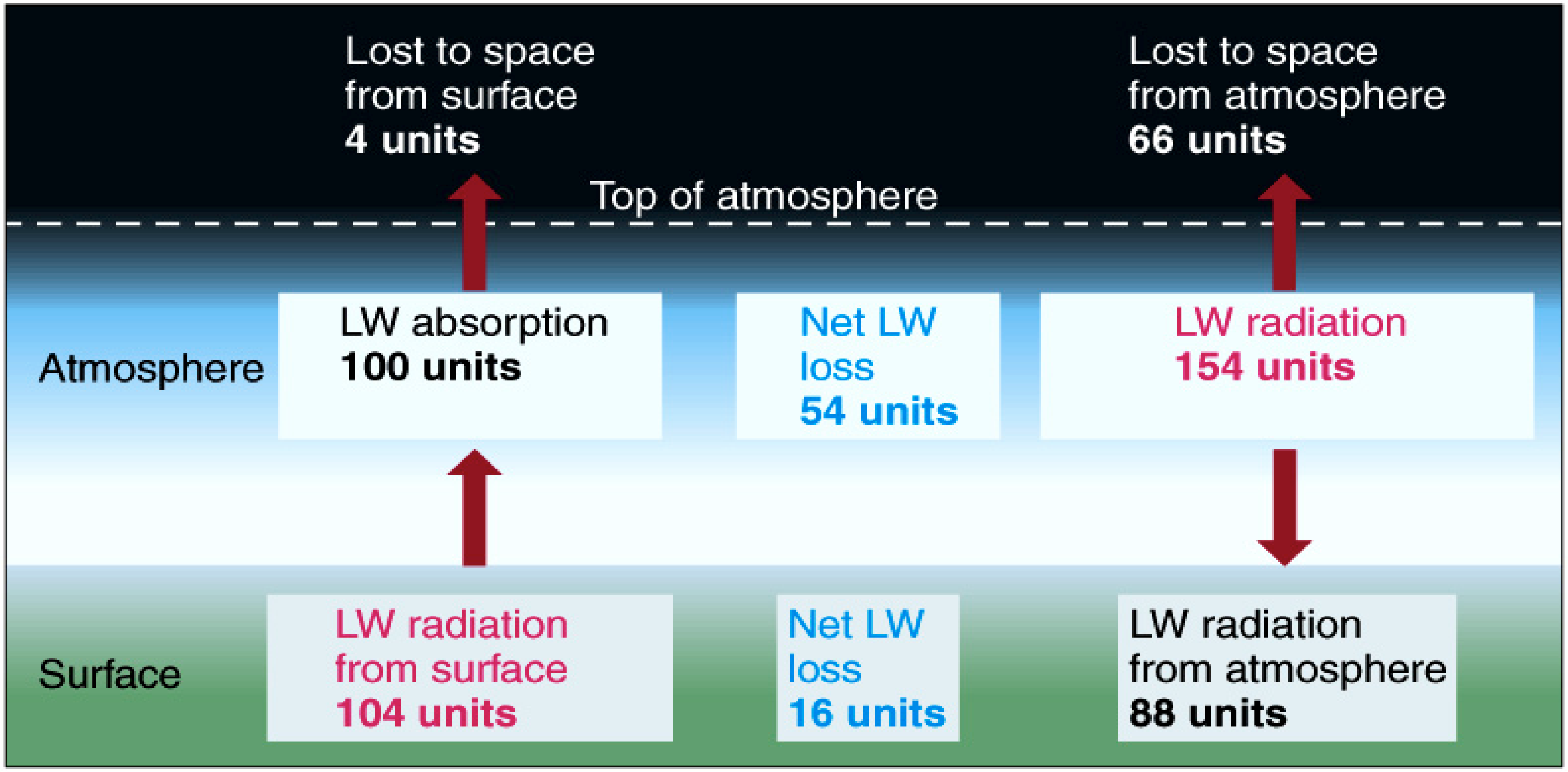
- Water droplets in clouds, typically larger than energy wavelengths, equally scatter wavelengths along the visible portion of the spectrum.
- Produces a white or gray appearance.
- No wavelength is especially affected.

Fate of Solar Radiation

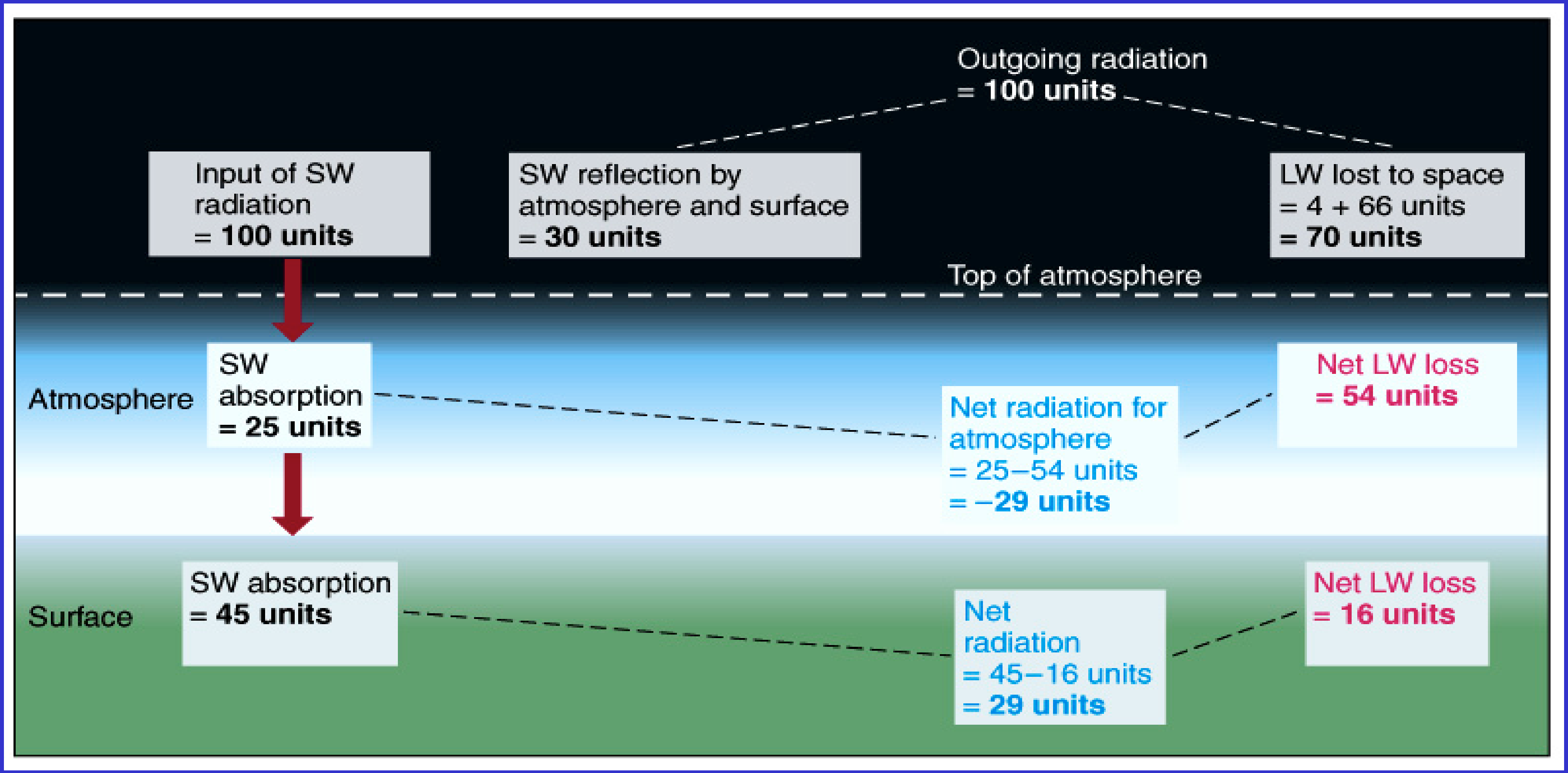


- Atmospheric reflection averages 25 units, 19 of which are reflected to space by clouds and 6 units which are back-scattered to space from atmospheric gases.
- The atmosphere absorbs another 25 units.
- Remaining 50 units are available for surface absorption and reflection.

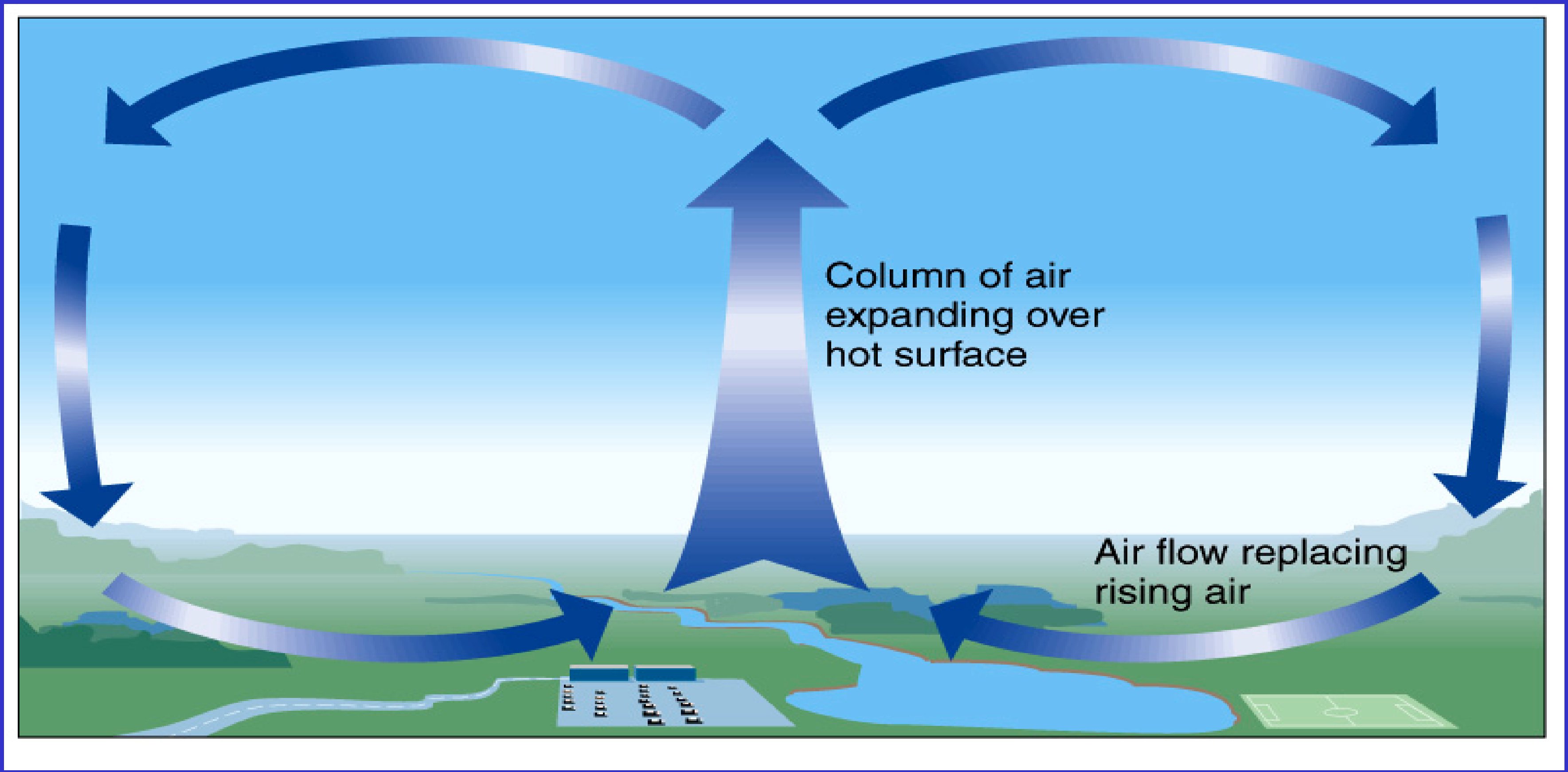
How Earth Loses Radiation to Space?



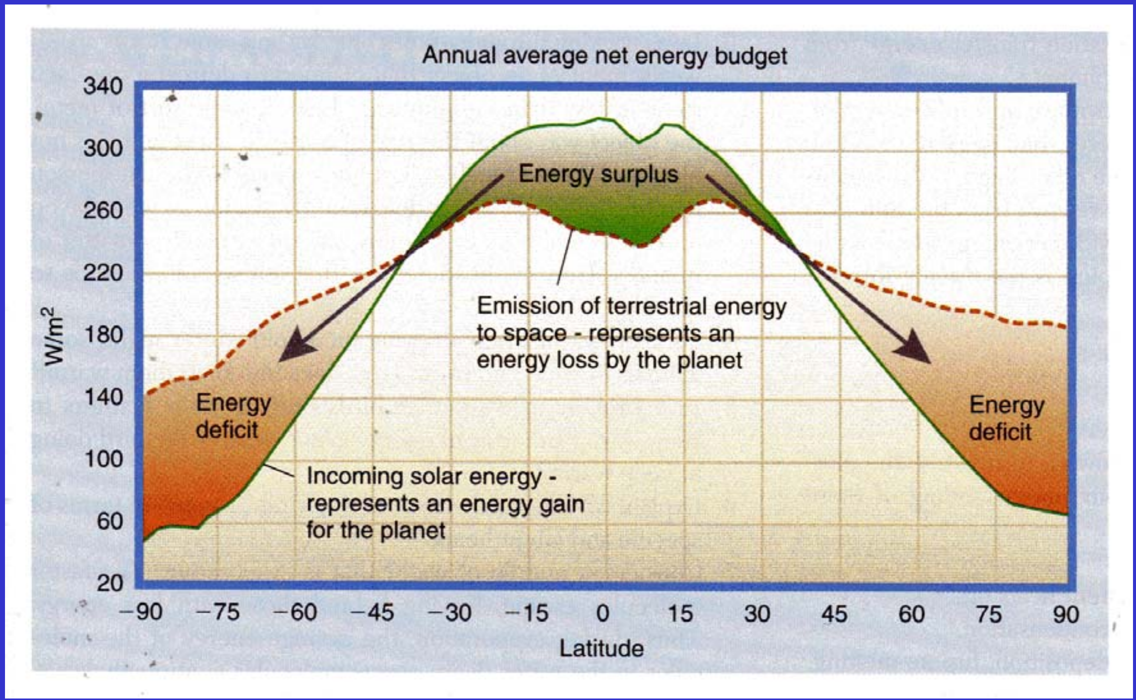
Global Energy Balance



Convection Balance the Energy btw Surface and Atmosphere



Latitudinal Variations of Net Energy

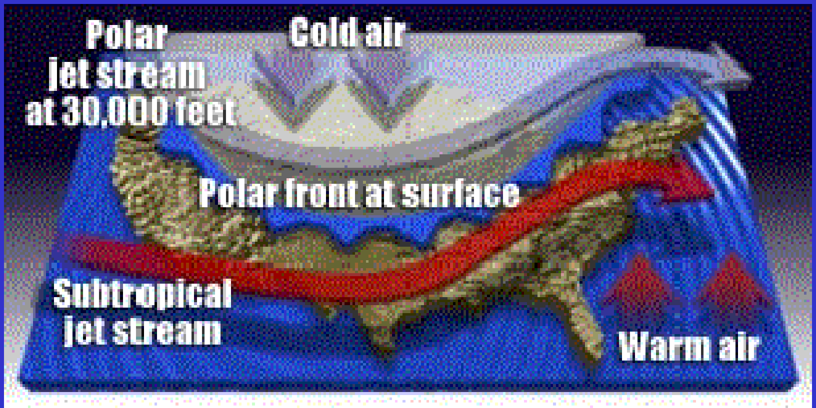


(from *Meteorology: Understanding the Atmosphere*)

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

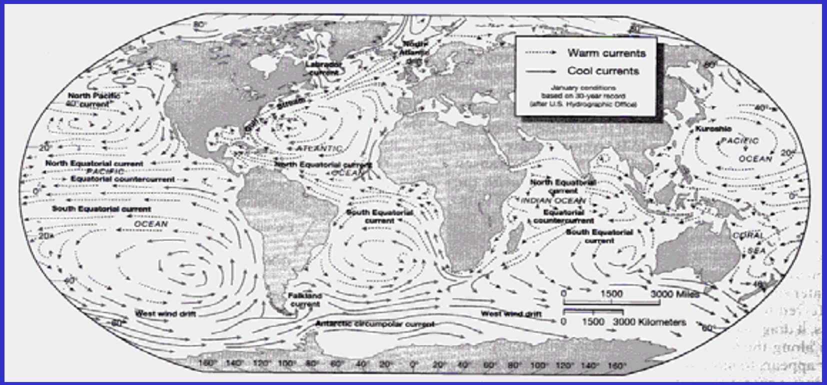
How Do Atmosphere and Ocean Transport Heat?

Atmospheric Circulation



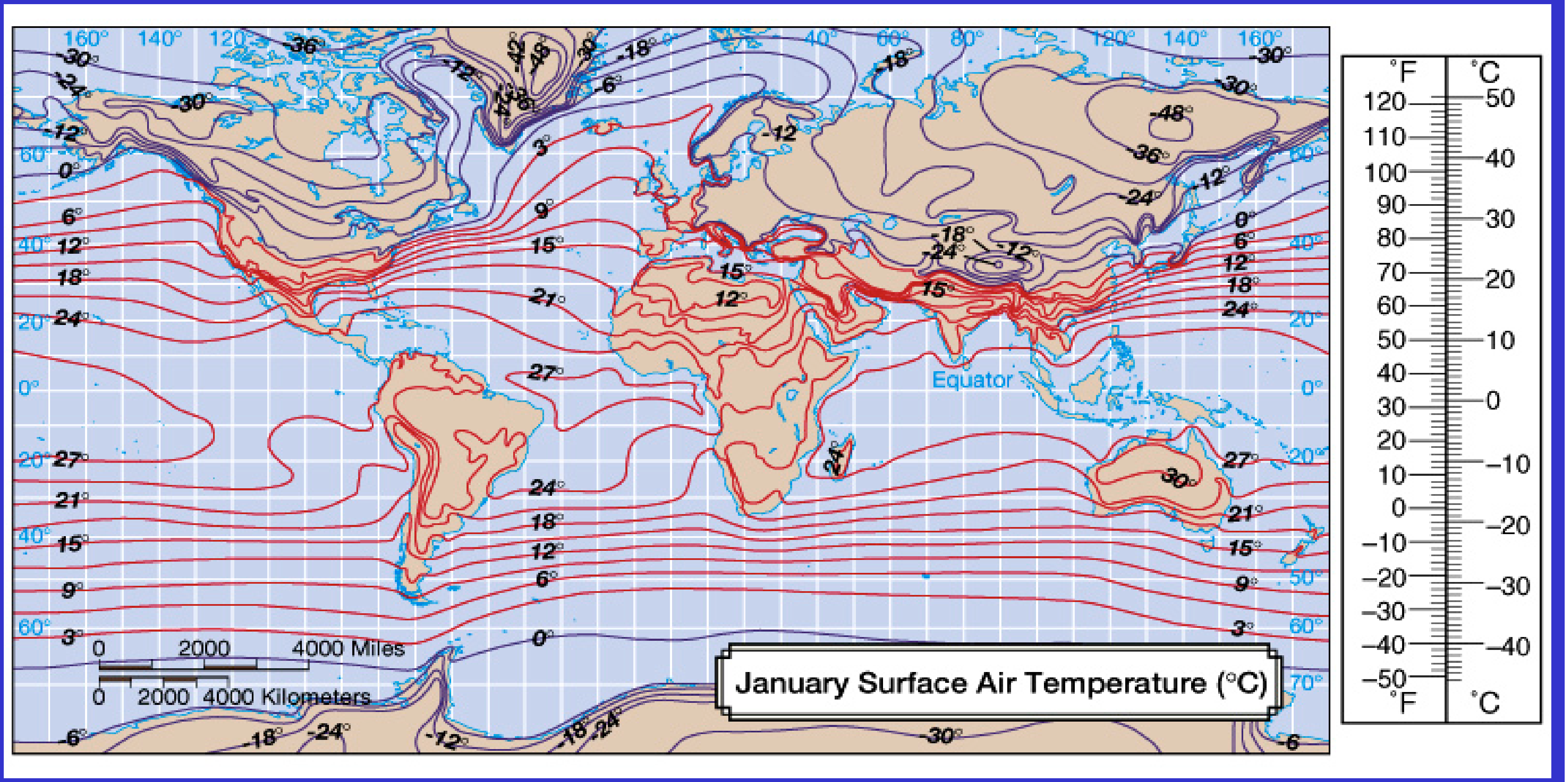
(from USA Today)

Ocean Circulation



(from *The Earth System*)

Isotherm



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