Radiation and Global Energy Balance

Energy (work) = Force × Length

1 joule (J) = 1 newton (N) × 1 meter (m)

Power = Energy / Time

watt (W) = J / s

Key topics:

1. Radiation
2. Heat transfer
3. Global radiative energy balance and its distributions

For radiation and the zenith angle, **see Hartmann, D.L. (1994), Global Physical Climatology, 411 pp., Academic Press. [p. 18-48; Appendix A, p347-349]** and **Bonan, G.B. (2008), Ecological Climatology, p. 41-50.**

For its use in land surface modeling, see http://www.cesm.ucar.edu/models/cesm1.0/clm/ and

Oleson, K.W., D.M. Lawrence, G.B. Bonan, M.G. Flanner, E. Kluzek, P.J. Lawrence, S. Levis, S.C. Swenson, P.E. Thornton, A. Dai, M. Decker, R. Dickinson, J. Feddema, C.L. Heald, F. Hoffman, J.-F. Lamarque, N. Mahowald, G.-Y. Niu, T. Qian, J. Randerson, S. Running, K. Sakaguchi, A. Slater, R. Stockli, A. Wang, Z.-L. Yang, Xi. Zeng, and Xu. Zeng, 2010: Technical Description of version 4.0 of the Community Land Model (CLM). NCAR Technical Note NCAR/TN-478+STR, National Center for Atmospheric Research, Boulder, CO, 257 pp. [p. 49-52]

Energy from the Sun

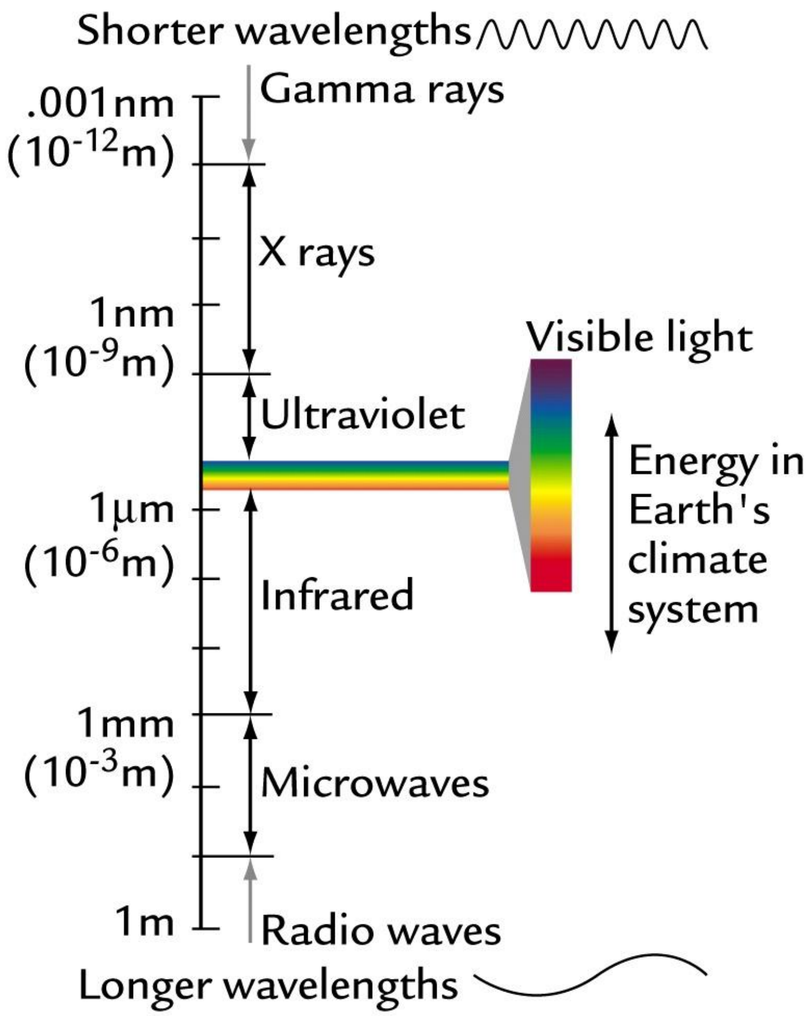
1. Characteristics

Travels through space (vacuum) in a speed of light

In the form of waves: Electromagnetic waves

In stream of particles (Photons)

Releases heat when absorbed



2. Electromagnetic spectrum

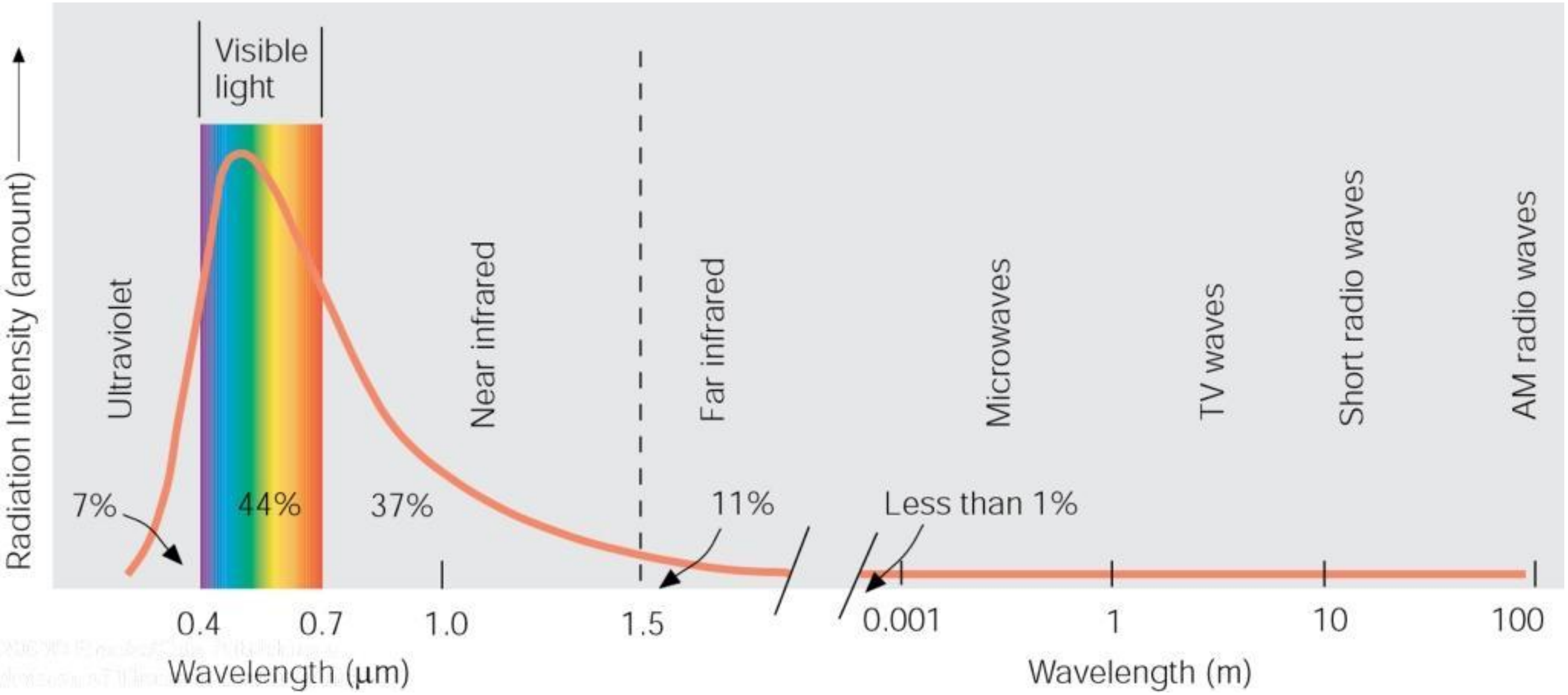
From short wavelength, high energy, gamma rays to long wavelength, low energy, radio waves

3. Importance to climate and climate change

Primary driving force of Earth's climate engine

Ultraviolet, Visible, Infrared

Sun’s Electromagnetic Spectrum



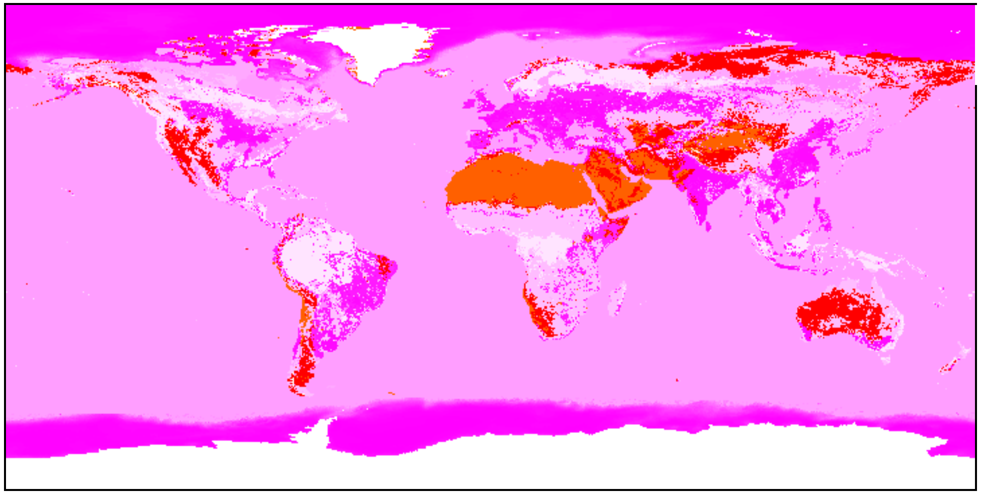
Solar radiation has peak intensities in the shorter wavelengths, dominant in the region we know as visible, thus shortwave radiation

Radiation

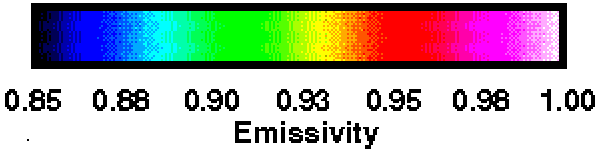
All objects above 0° K release radiation, and its heat energy value increases to the 4th power of its temperature (Stefan-Boltzmann Law).

Blackbody radiation: $E_{BB} = \sigma T^4$ unit: $W\ m^{-2}$

$\sigma = 5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$; T unit: K



Broadband Emissivity

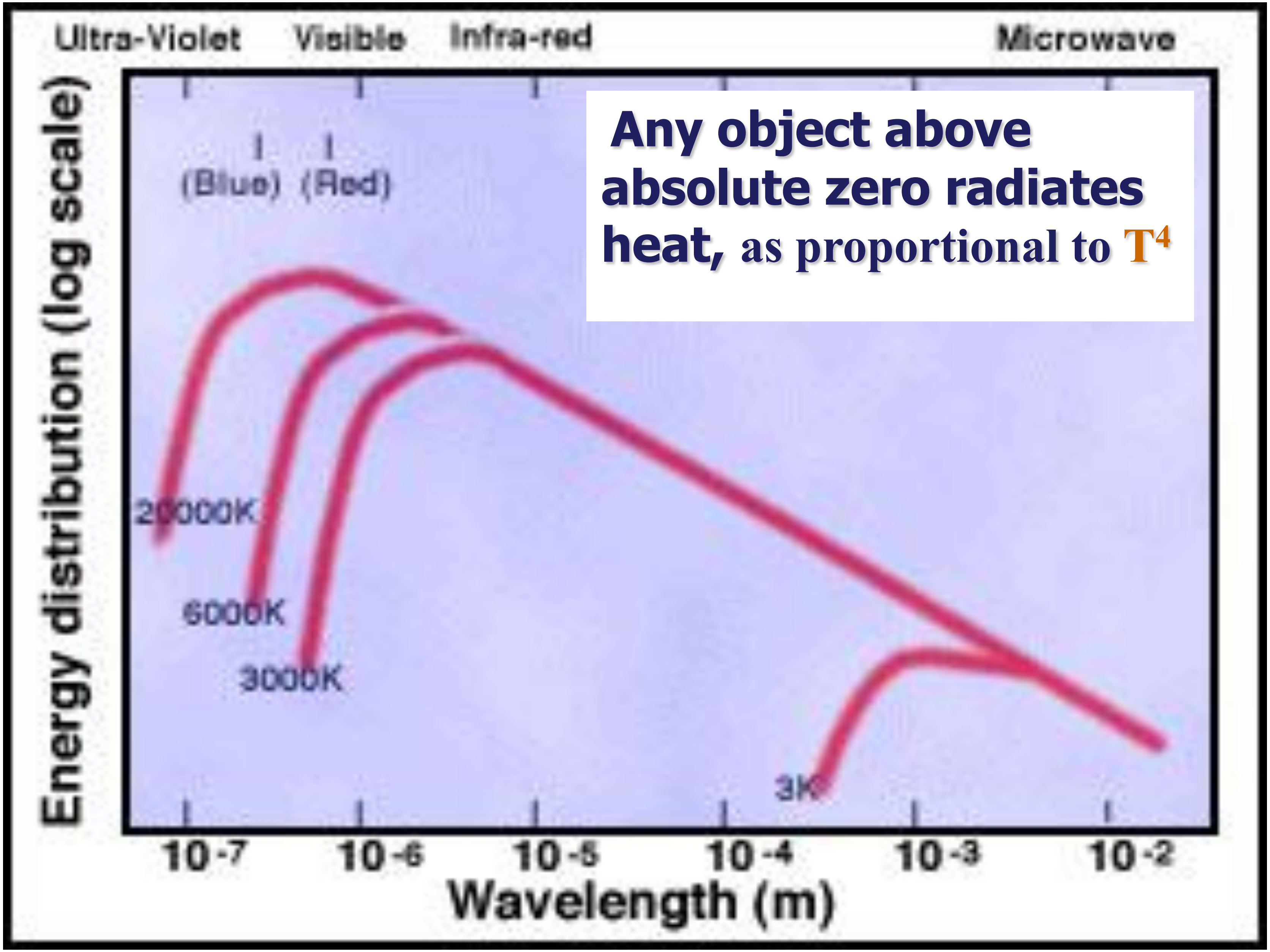


http://www-surf.larc.nasa.gov /surf/pages/ems_bb.html

Emissivity = the ratio of the actual emission of a body or volume of gas to the blackbody emission at the same temperature

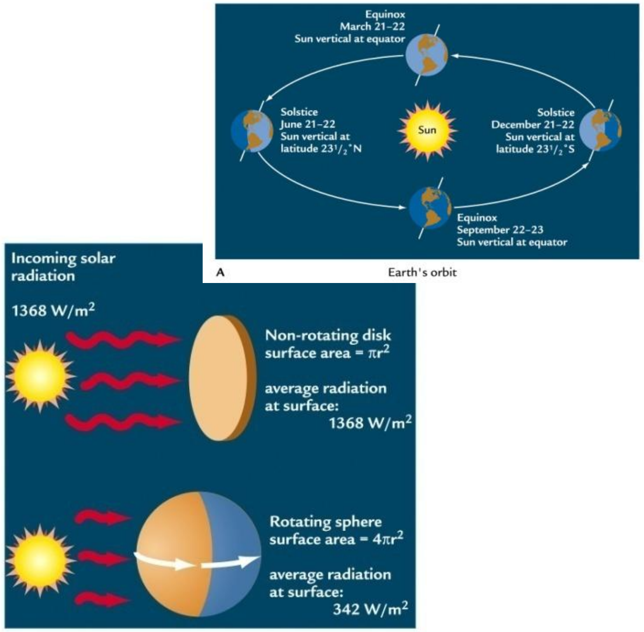
$$E_R = \varepsilon \sigma T^4 \rightarrow \varepsilon = E_R / (\sigma T^4)$$

Blackbody Radiation Curves



Any object above absolute zero radiates heat, as proportional to T^4

Energy Flux, Solar Constant, Emission Temperature



Solar luminosity: $L_0 = 3.9 \times 10^{26}$ J/s = 3.9×10^{26} W

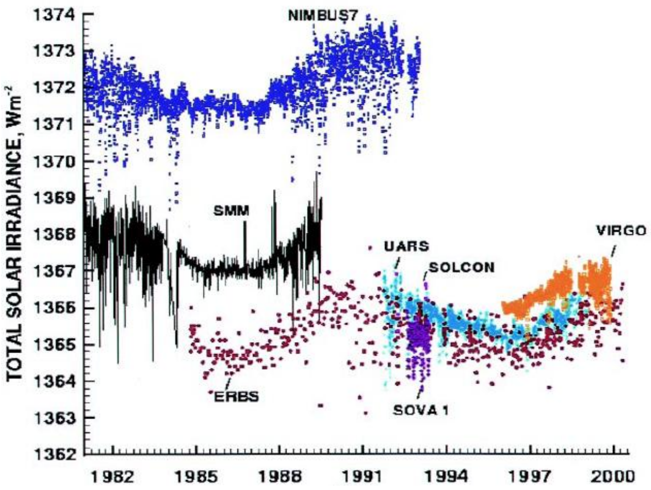
Energy conservation: L_0 at the Sun's photosphere = L_0 at any distance d from the Sun (1st law of thermodynamics dQ=dU – dW)

Flux density = flux / area = $L_0 / (4\pi d^2)$ = solar constant [Note that both L_0 and d are large numbers, and a tiny change in their precision (e.g. due to rounding) can affect S_0 values]

Earth's solar constant $S_0 = 1367 \pm 2$ Wm^{-2}; instrumental measurements began in late 1970s; 11-yr solar cycle

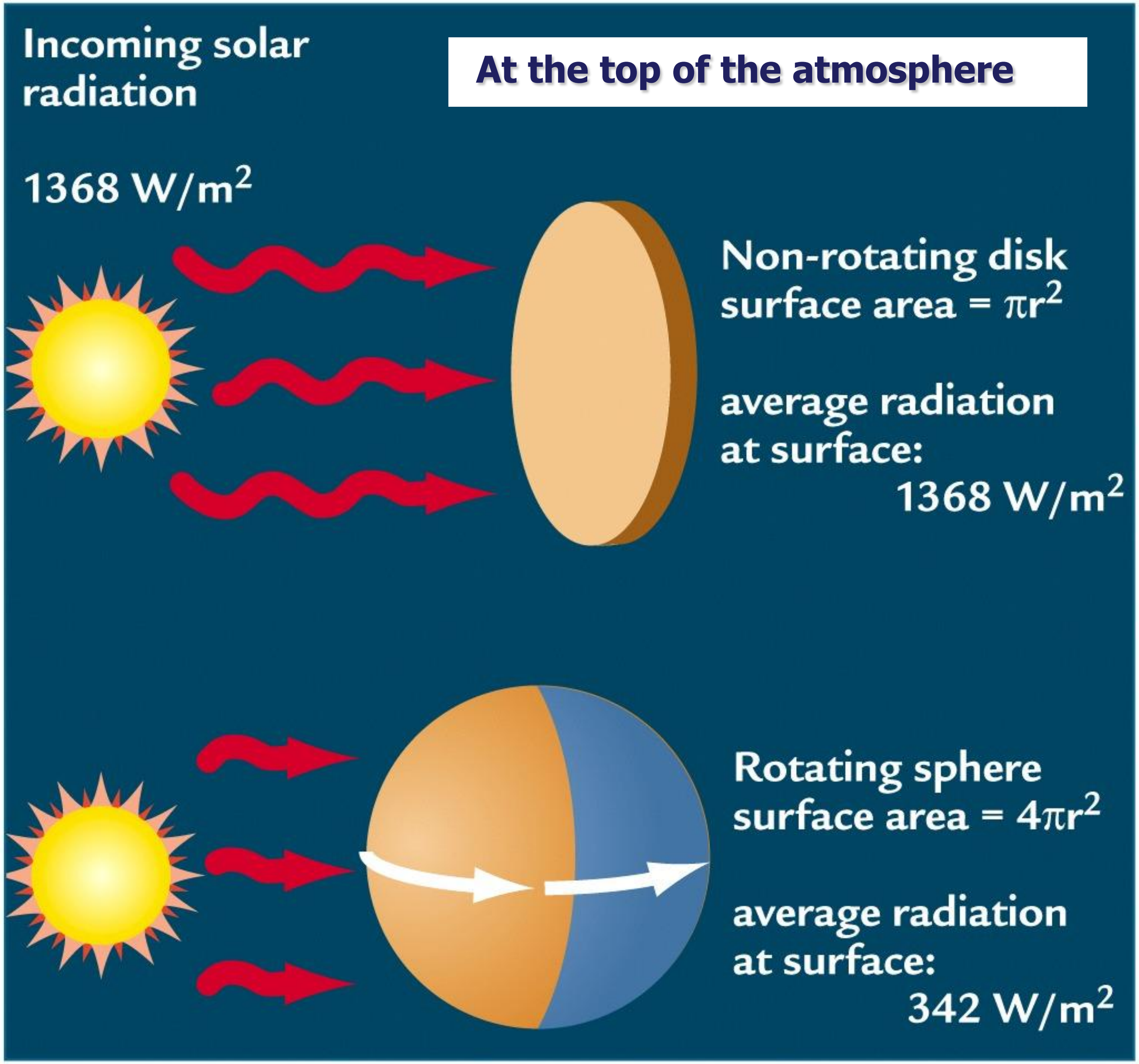
Emission temperature of the Sun = 5796 K

Emission temperature of a planet: solar radiation absorbed = planetary radiation emitted



Asrar et al. (2001) BAMS (Fig. 5)

Incoming Solar Radiation (Insolation)



Energy Flux, Solar Constant, Emission Temperature (continued)

Absorbed solar radiation = $S_0 (1 - \alpha) \pi r^2$

Emitted terrestrial radiation = $\sigma T^4 4\pi r^2$

Both are equal: $S_0 (1 - \alpha) /4 = \sigma T^4$

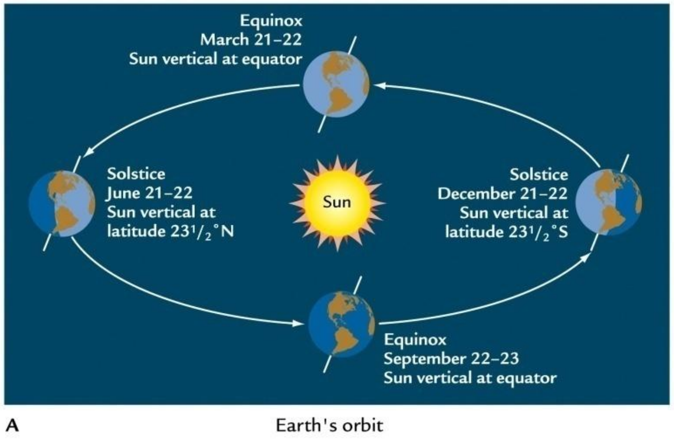
Emission temperature: $T = [(S_0/4) (1 - \alpha) /\sigma]^{1/4}$

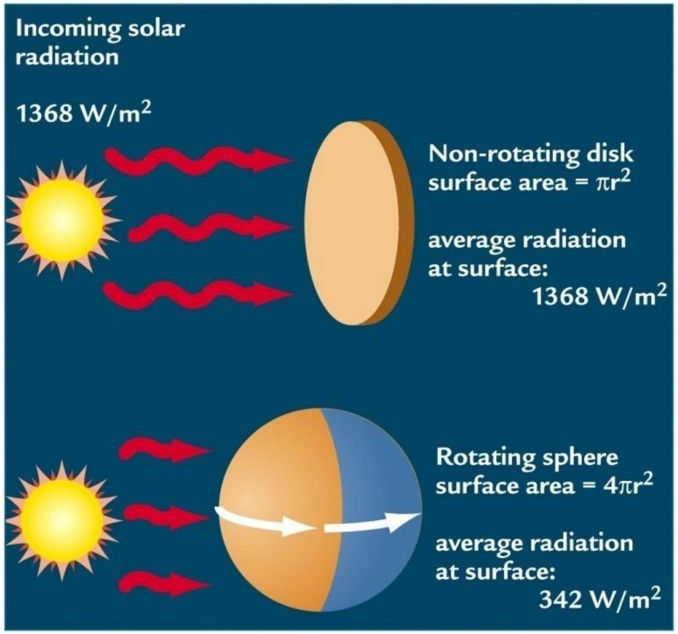
where $S_0/4$ = the globally averaged insolation at the TOA = 1368 / 4 = 342 Wm^{-2}, and the factor of 4 is the ratio of the global surface area of a sphere to its shadow area, which is the area of a circle with the same radius.

α = the planetary albedo for Earth = 30% = 0.30

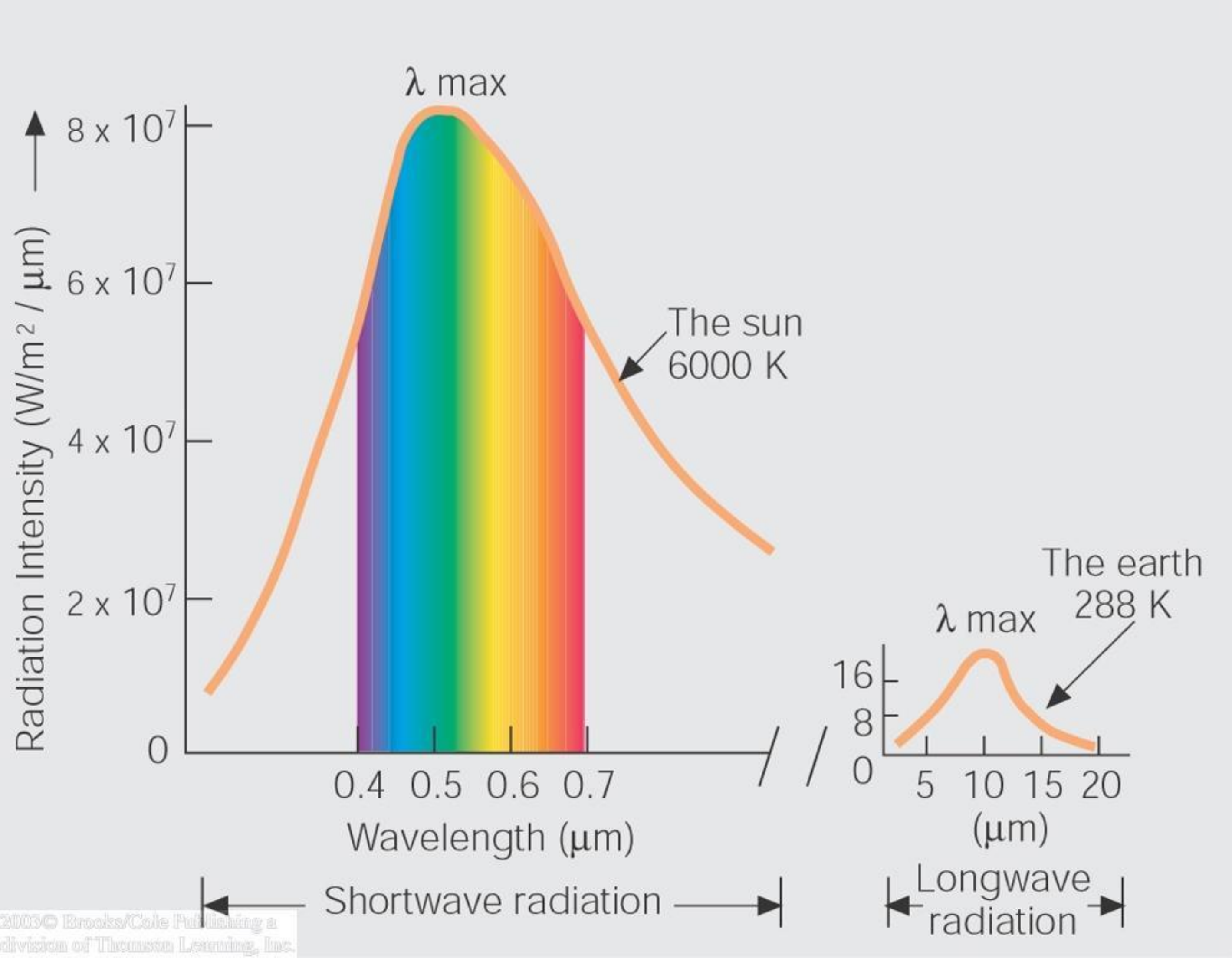
Substituting these values into the equation for T, we have Earth's emission temperature

$T = 255\ K = -18°C$



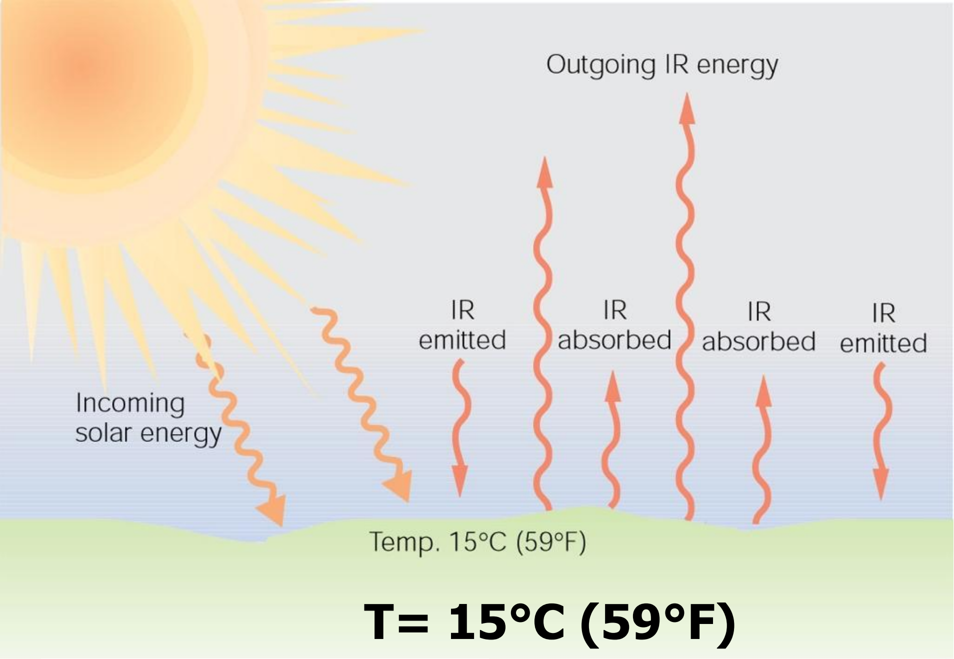


Longwave & Shortwave Radiation



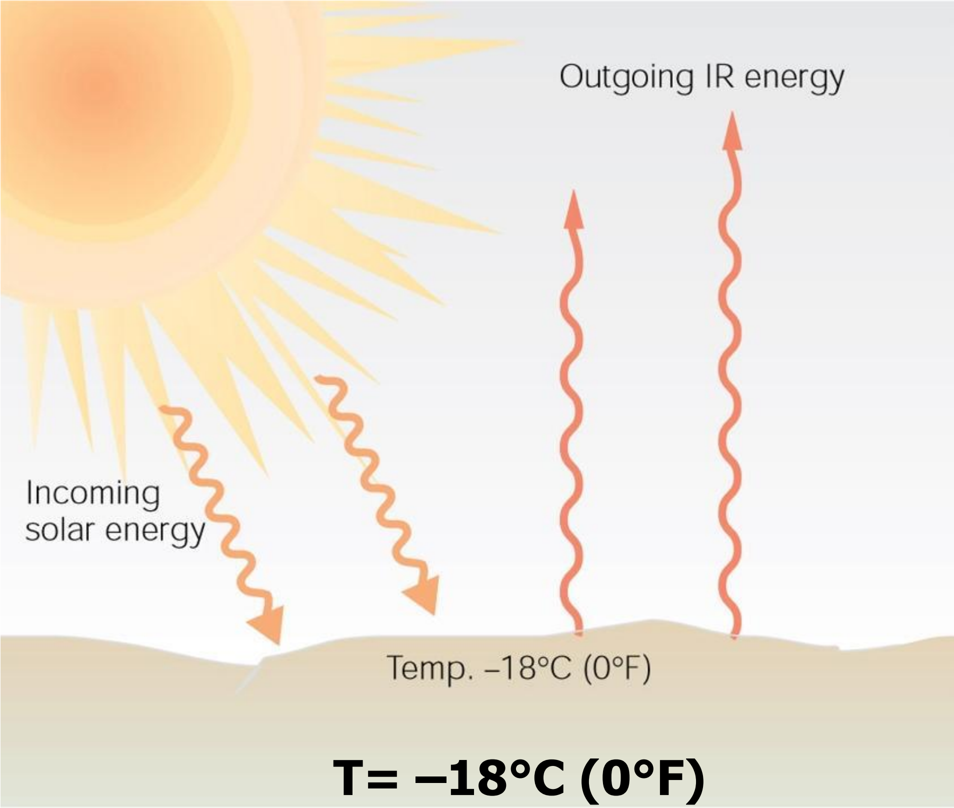
The hot sun radiates at shorter wavelengths that carry more energy, and the fraction absorbed by the cooler earth is then re-radiated at longer wavelengths.

Earth’s Average Radiating Temperature?



T= 15°C (59°F)

Ground-based Measurements



T= –18°C (0°F)

Space-based Measurements

Greenhouse Effect!

Caused by Greenhouse Gases!

Greenhouse Gases

✓ What are they?

Water vapor (H_2O)

Carbon dioxide (CO_2)

Methane (CH_4)

Ozone (O_3)

Chlorofluorocarbons (CFC’s)

Nitrous oxide (N_2O)

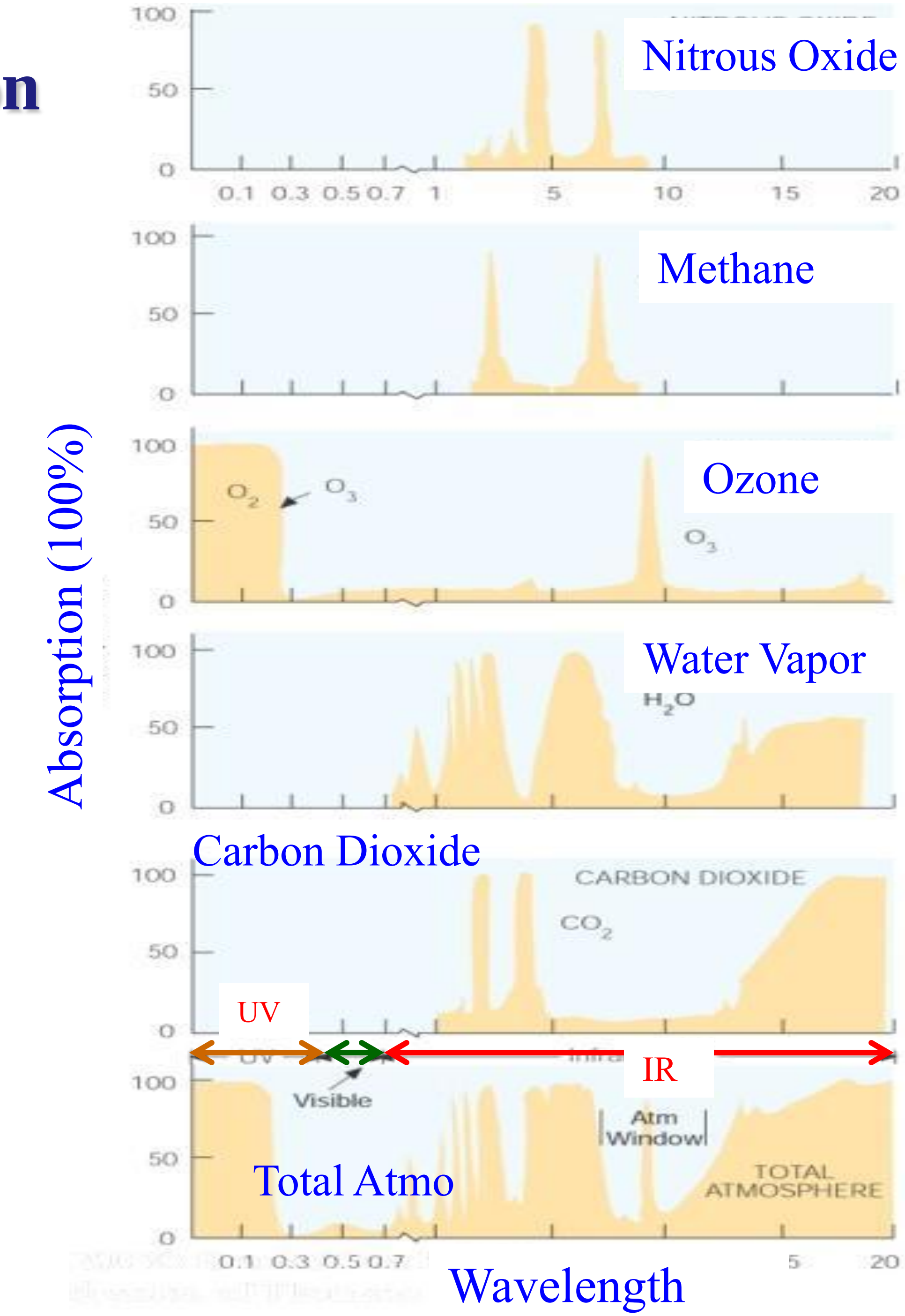
✓ Water vapor accounts for 60% of the atmospheric greenhouse effect, CO_2 26%, and the remaining greenhouse gases 14%.

✓ CO_2 contributes most (55-60%) to the **anthropogenic greenhouse effect**, and methane is a distant second (16%).

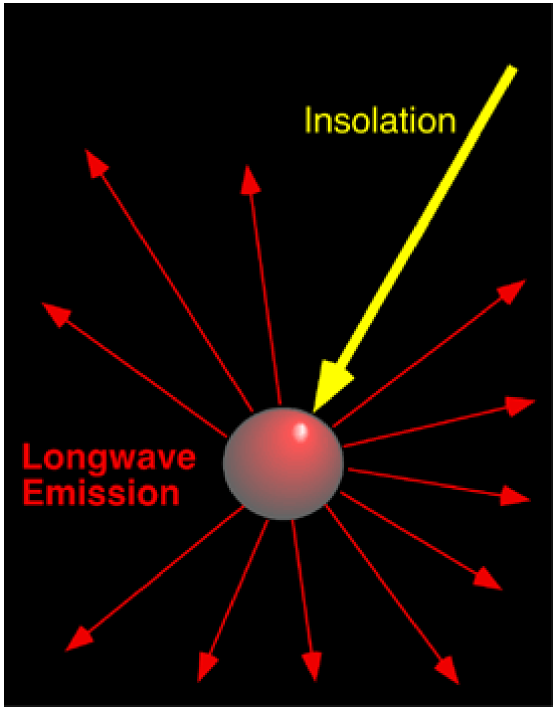
✓ CFCs cause the strongest greenhouse warming on a molecule-for-molecule basis.

Atmospheric Absorption

Solar radiation passes rather freely through earth's atmosphere, but earth's re-emitted longwave energy either fits through a narrow window or is absorbed by greenhouse gases and re-radiated toward earth.

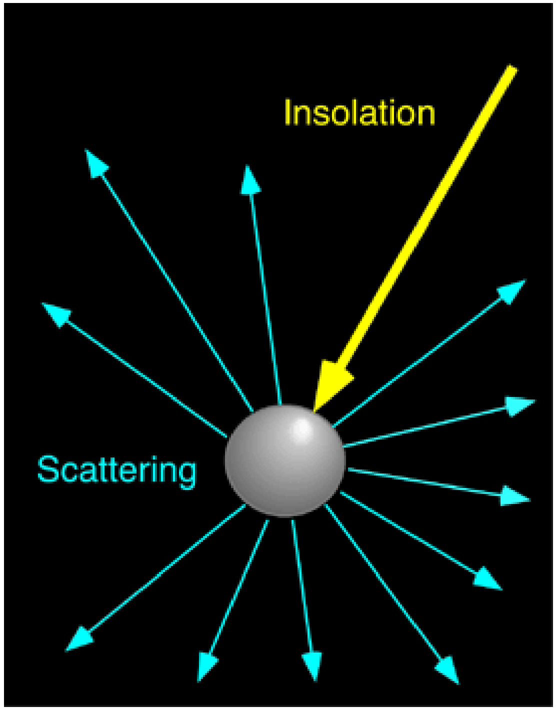


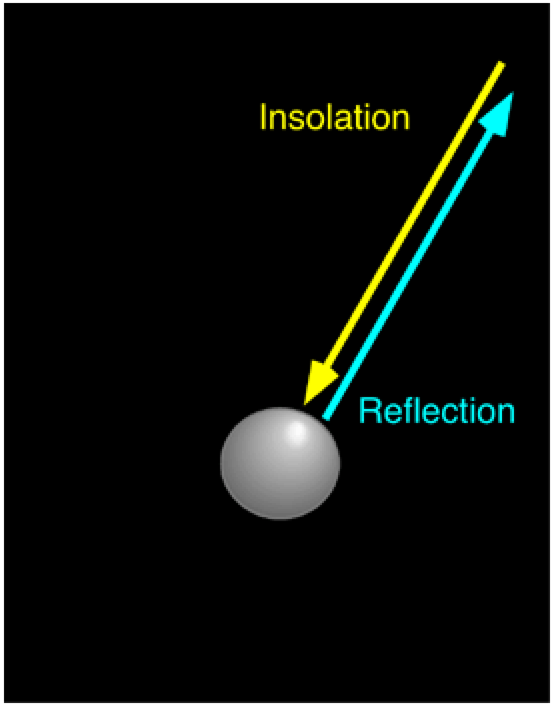
Absorption, Scattering and Reflectance (Albedo)



Temperature increases

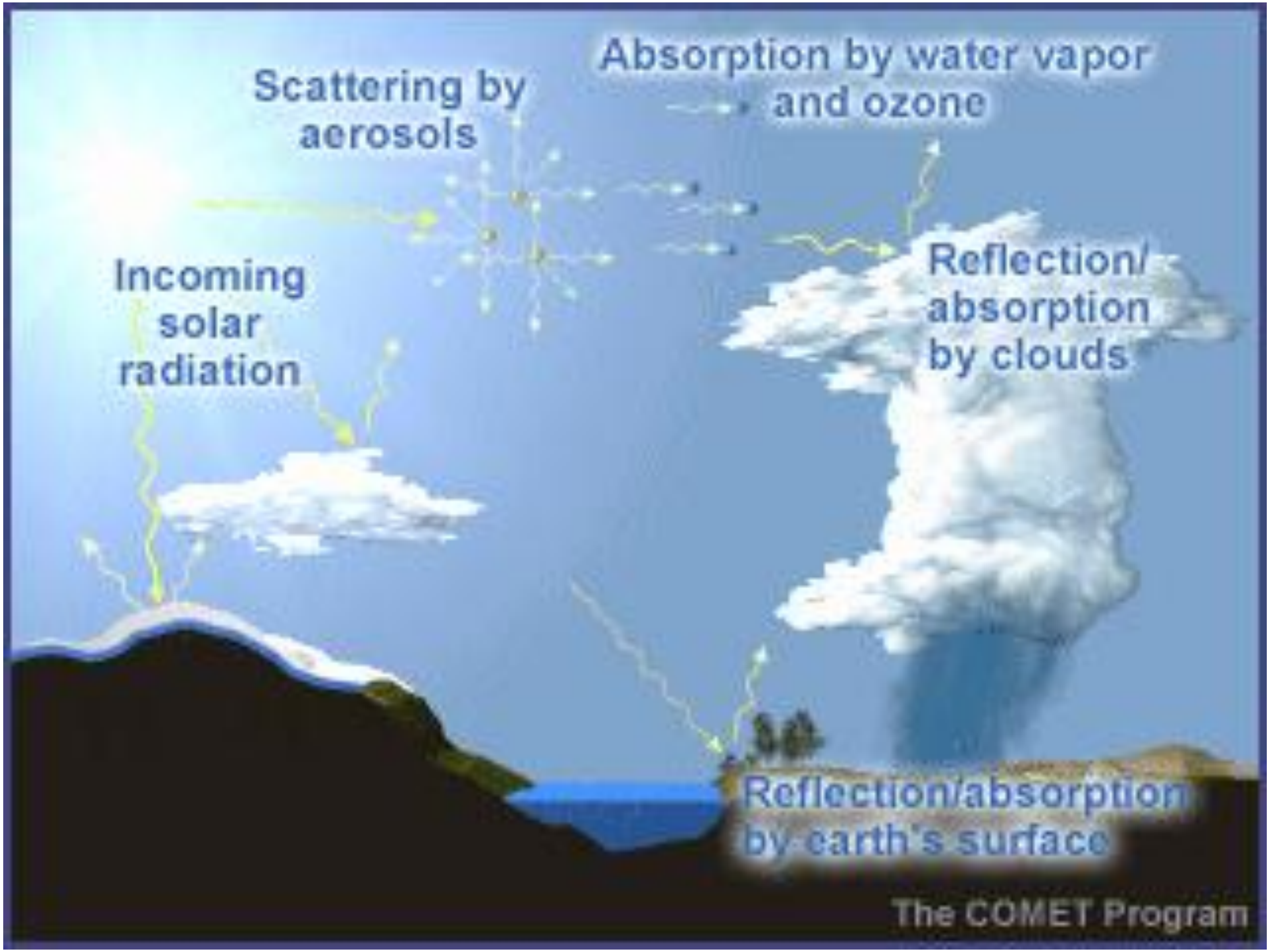
All directions



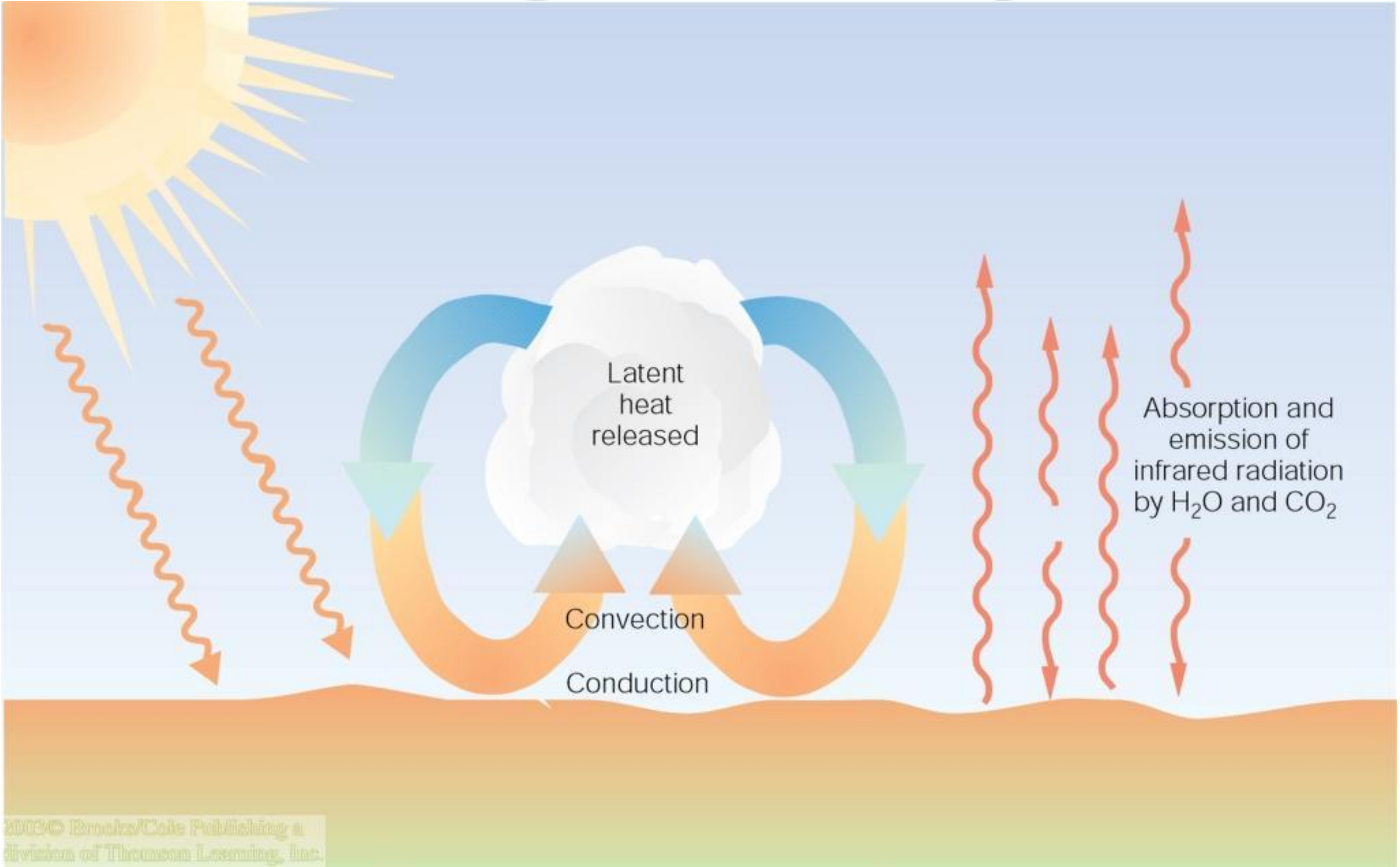


Backwards

Absorption, Scattering and Reflectance (Albedo)



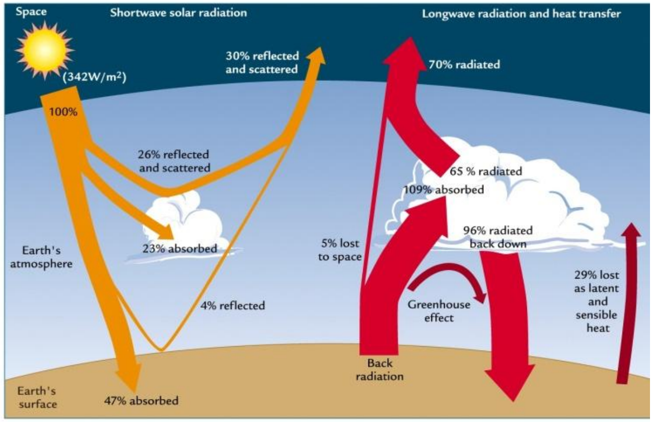
Warming Earth's Atmosphere

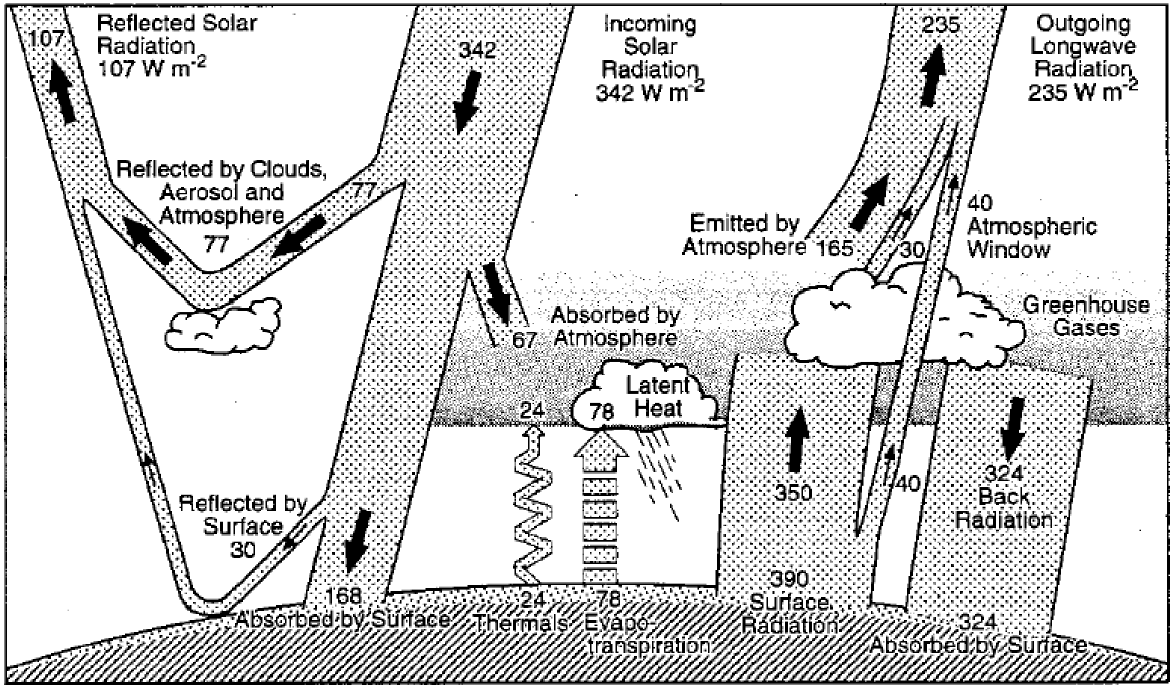


Solar radiation passes first through the upper atmosphere, but only after absorption by earth's surface does it generate sensible heat to warm the ground and generate longwave energy.

This heat and energy at the surface then warms the atmosphere from below.

Earth’s Radiation Budget (Global Annual Average)



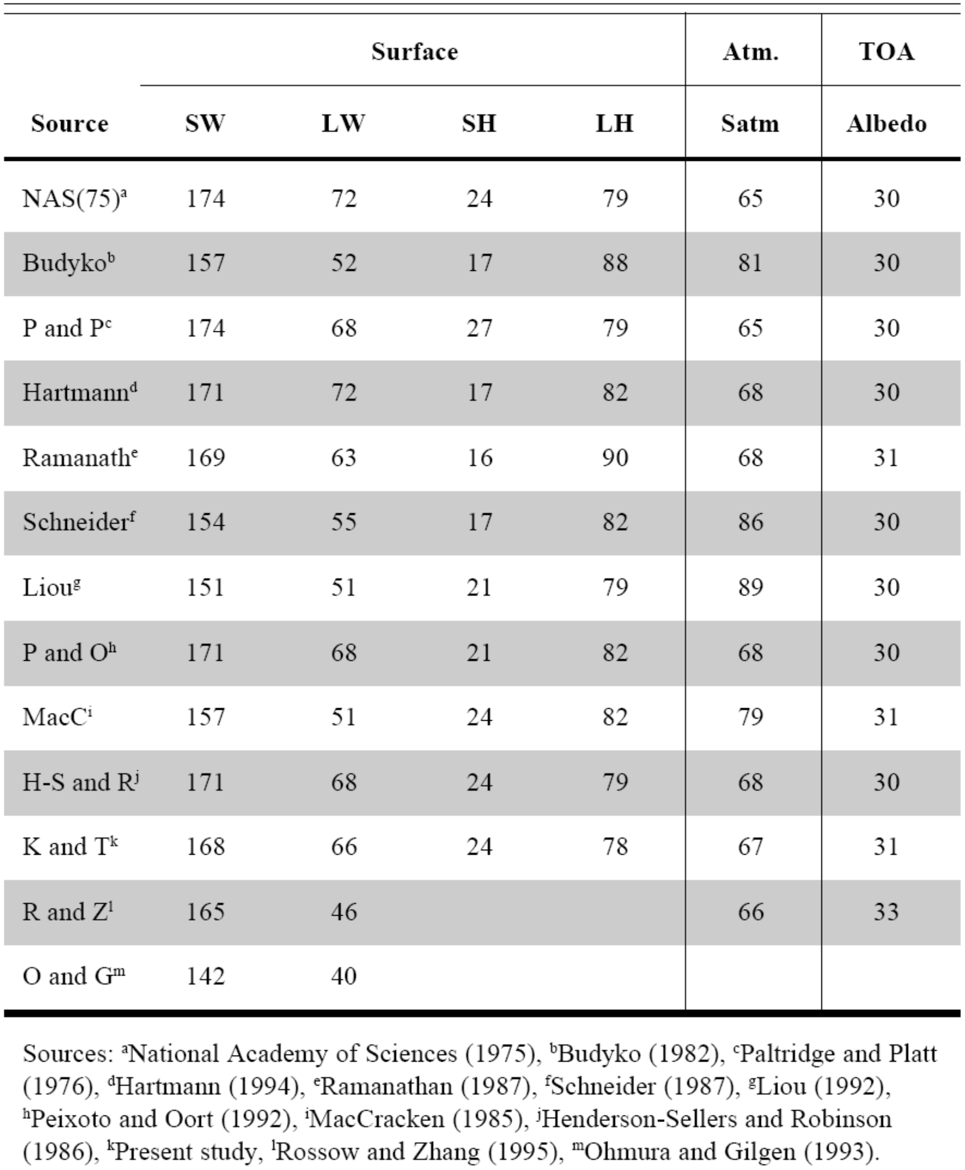


Kiehl and Trenberth (1997) BAMS (Fig. 7)

Earth reflects 30% directly back to space, absorbs about 20% in the atmosphere, and absorbs about 50% at the surface.

Earth’s lower atmosphere is warmed by radiation, conduction, convection of sensible heat and latent heat.

Comparison of Different Estimates



	Surface				Atm.	TOA
Source	**SW**	**LW**	**SH**	**LH**	**Satm**	**Albedo**
NAS(75)[a]	174	72	24	79	65	30
Budyko[b]	157	52	17	88	81	30
P and P[c]	174	68	27	79	65	30
Hartmann[d]	171	72	17	82	68	30
Ramanath[e]	169	63	16	90	68	31
Schneider[f]	154	55	17	82	86	30
Liou[g]	151	51	21	79	89	30
P and O[h]	171	68	21	82	68	30
MacC[i]	157	51	24	82	79	31
H-S and R[j]	171	68	24	79	68	30
K and T[k]	168	66	24	78	67	31
R and Z[l]	165	46			66	33
O and G[m]	142	40				

Sources: [a]National Academy of Sciences (1975), [b]Budyko (1982), [c]Paltridge and Platt (1976), [d]Hartmann (1994), [e]Ramanathan (1987), [f]Schneider (1987), [g]Liou (1992), [h]Peixoto and Oort (1992), [i]MacCracken (1985), [j]Henderson-Sellers and Robinson (1986), [k]Present study, [l]Rossow and Zhang (1995), [m]Ohmura and Gilgen (1993).

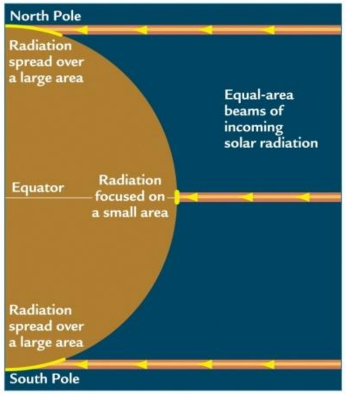
TABLE 1. Summary of the earth energy budget estimates, selected to be those with albedos near 30%. All fluxes are based on an insolation of 342 W m^{-2}. Here, SW is the net (down minus up) shortwave flux at the surface, LW is the net (up minus down) longwave flux at the surface, SH is the surface sensible heat, LH is the surface latent heat flux, and Satm is the shortwave absorbed flux in the atmosphere. Albedo is the planetary albedo in percent.

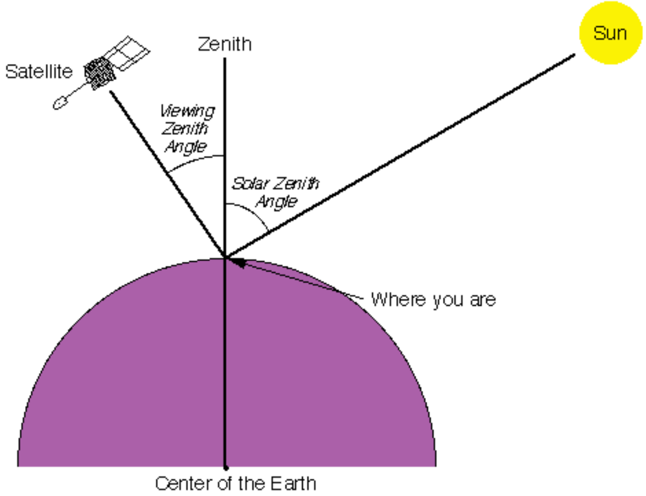
About 80% of Earth surface’s net radiation is used in evaporation.

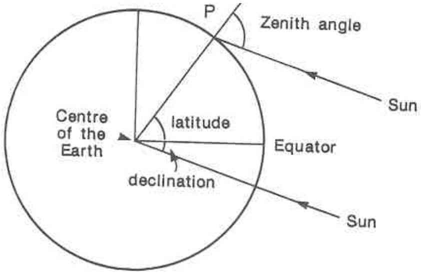
Kiehl and Trenberth (1997) BAMS (Fig. 7)

Unequal Radiation on a Sphere

Insolation is stronger in the tropics (low latitudes) than in the polar regions (high latitudes).







Solar flux (at TOA) per unit surface area

$Q = S_0 (d_m/d)^2 \cos\theta$

d_m = mean sun-earth distance

d = actual sun-earth distance

θ= the solar zenith angle, which depends on the latitude (φ), season (δ), and time of day (h).

$\cos\theta = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos h$

[See Appendix A in Hartmann (1994) for derivation]

At sunrise or sunset (when θ =90°),

$\cos h_0 = -\tan\varphi \tan\delta$; $h_0 = \cos^{-1}(-\tan\varphi \tan\delta)$

Daylight hours= $2 \times h_0 \times 24 / (2\pi) = 24 h_0 / \pi$ where h_0 in radians

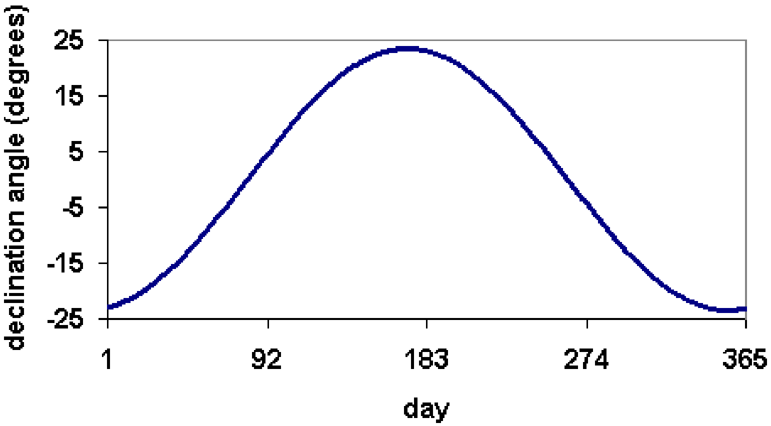
Averaged daily insolation at TOA

$Q_{day} = (S_0 / \pi)(d_m/d)^2 [h_0 \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin h_0]$

At solar noon (h =0), θ = φ – δ (basis for navigators traversing the oceans!)

Unequal Radiation on a Sphere (continued)

δ = the declination angle = the latitude of the point on the surface of Earth directly under the sun at noon;



Currently, δ varies between 23.45 (June 21) and -23.45 (December 21). This indicates that the sun is directly overhead at locations between 23.45° north and 23.45° south twice a year and the sun is never overhead at higher latitudes. At locations north of the Tropic of Cancer, the sun always appears in the south, while at locations south of the Tropic of Capricorn, the sun always appears to the north.

$\delta = 0.4093 \sin(2\pi j / 365 - 1.405)$ [in radians],
where j is calendar day, = 1 (January 1), 365 (December 31).

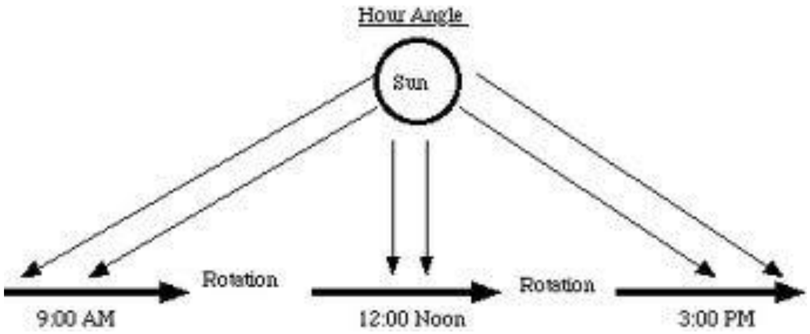
Alternatively, for δ, see Hartmann, equation (A.6), p. 348-349; Oleson, p. 49-52.

Unequal Radiation on a Sphere (continued)

h = the hour angle = the longitude of the subsolar point relative to its position at noon

h = 0, the sun straight overhead, <0 before local noon, >0 in the afternoon. In one 24 hour period, the hour angle changes by 360 degrees (i.e. one revolution).

Hour Angle in Degree	Solar Time
…	…
-90	6 hours before Solar Noon
-75	5 hours before Solar Noon
-60	4 hours before Solar Noon
-45	3 hours before Solar Noon
-30	2 hours before Solar Noon
-15	1 hour before Solar Noon
0	Sun overhead i.e. Solar Noon
15	1 hour after Solar Noon
30	2 hours after Solar Noon
45	3 hours after Solar Noon
60	4 hours after Solar Noon
75	5 hours after Solar Noon
90	6 hours after Solar Noon
...	...



$(d_m/d)^2 = f_e = 1 + 0.033 \cos(2\pi j / 365)$, the eccentricity factor or the relative distance between Earth and Sun. Alternatively, see Hartmann, equation (A.7), p. 349-349.

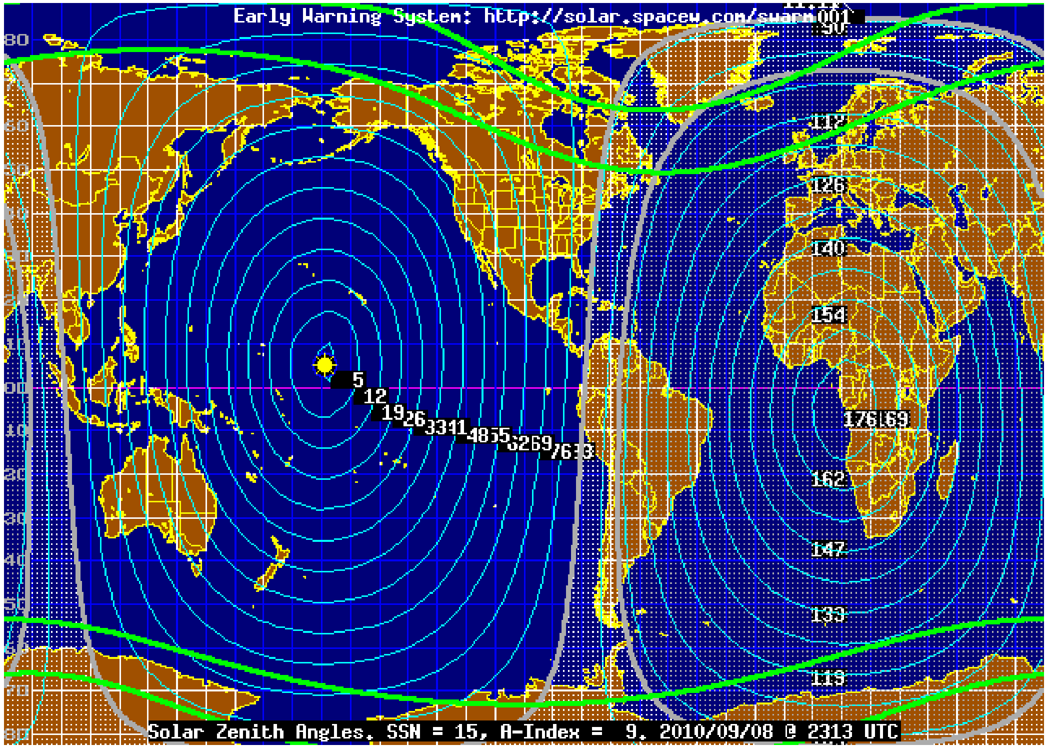
The day length will be 12 hours if either $\tan(\varphi) = 0$ (the equator on all days) or $\tan(\delta) = 0$ (the equinoxes at all latitudes except the Poles). The latitude of the polar night may be found by setting $h_0 = 0$ in the above equation, leading to $90^o - |\delta| = \varphi$ in the winter hemisphere.

At the Poles, $\cos(\varphi) = 0$, $\sin(\varphi) = 1$, and $\cos(\theta) = \sin(\delta)$ or (in degrees): $90^o - \theta = \delta$. Hence, at these points the elevation angle (i.e., $90 - \theta$) of the sun always equals the declination angle and during 6 months of daylight the sun simply circles around the horizon, never rising more than 23°27' above it.

Unequal Radiation on a Sphere (continued)

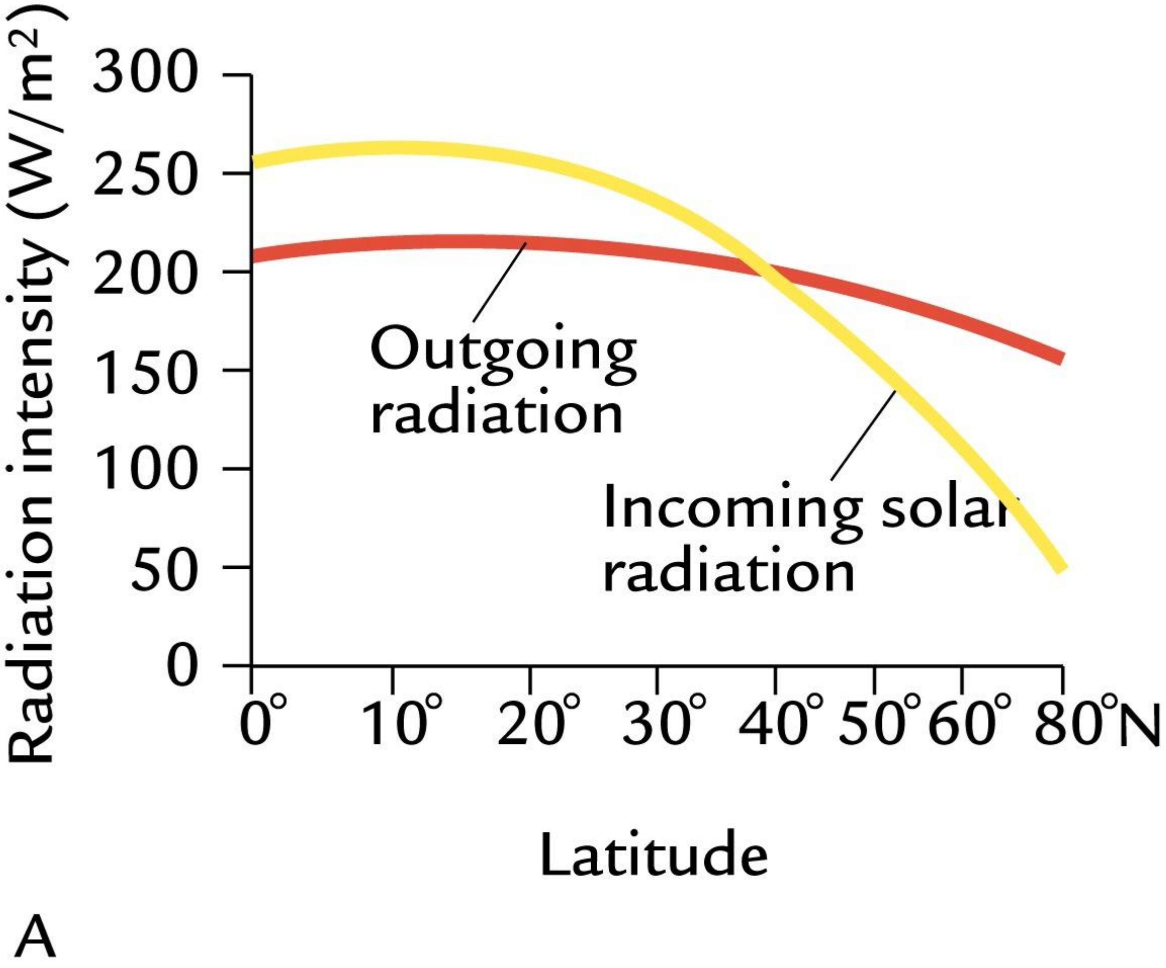
Near-Real-Time Map of Solar Zenith Angles: http://www.spacew.com/www/zenith.html

This map shows you precisely how high in the sky the Sun is at any location around the world. The contours of this map are given in degrees and refer to the distance the Sun is away from the zenith (or that point directly overhead). A contour labelled 10 degrees would define the regions of the world where the Sun is exactly 10 degrees away from the zenith (or in other words, the Sun would be 10 degrees [or about an outstretched hand-span] away from the point directly above your head). A contour labelled 45 degrees would define regions of the world where the Sun is half-way between the horizon and the zenith. A contour labelled 90-degrees would define all of those regions around the world where the Sun is exactly on the horizon (rising or setting). Contours greater than 90 degrees indicate regions of the world where the Sun is below the horizon.



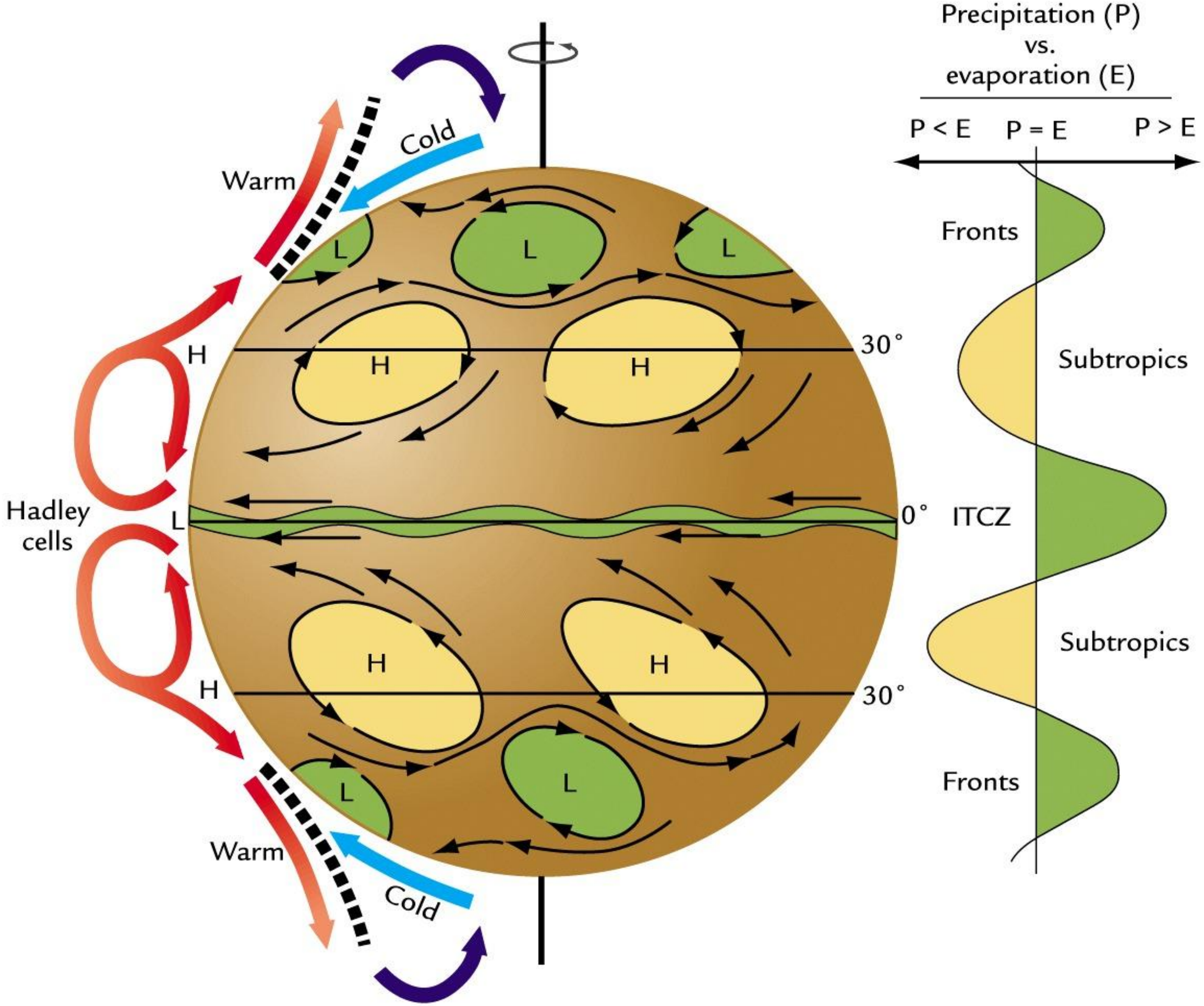
See the programming assignment for further understanding.

Why do we global wind patterns (general circulation)?

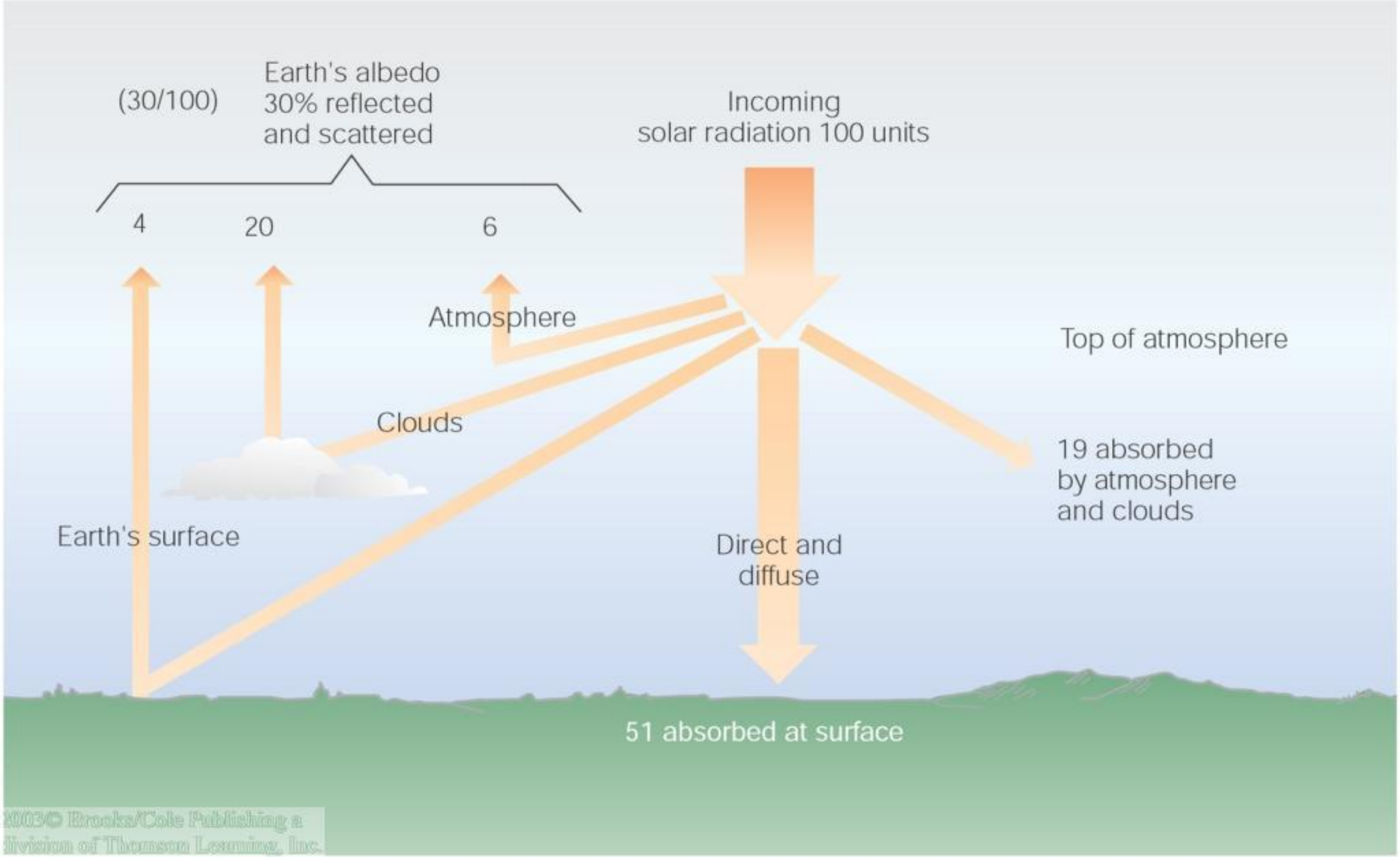


Unequal heating of tropics and poles

General Circulation of the Atmosphere

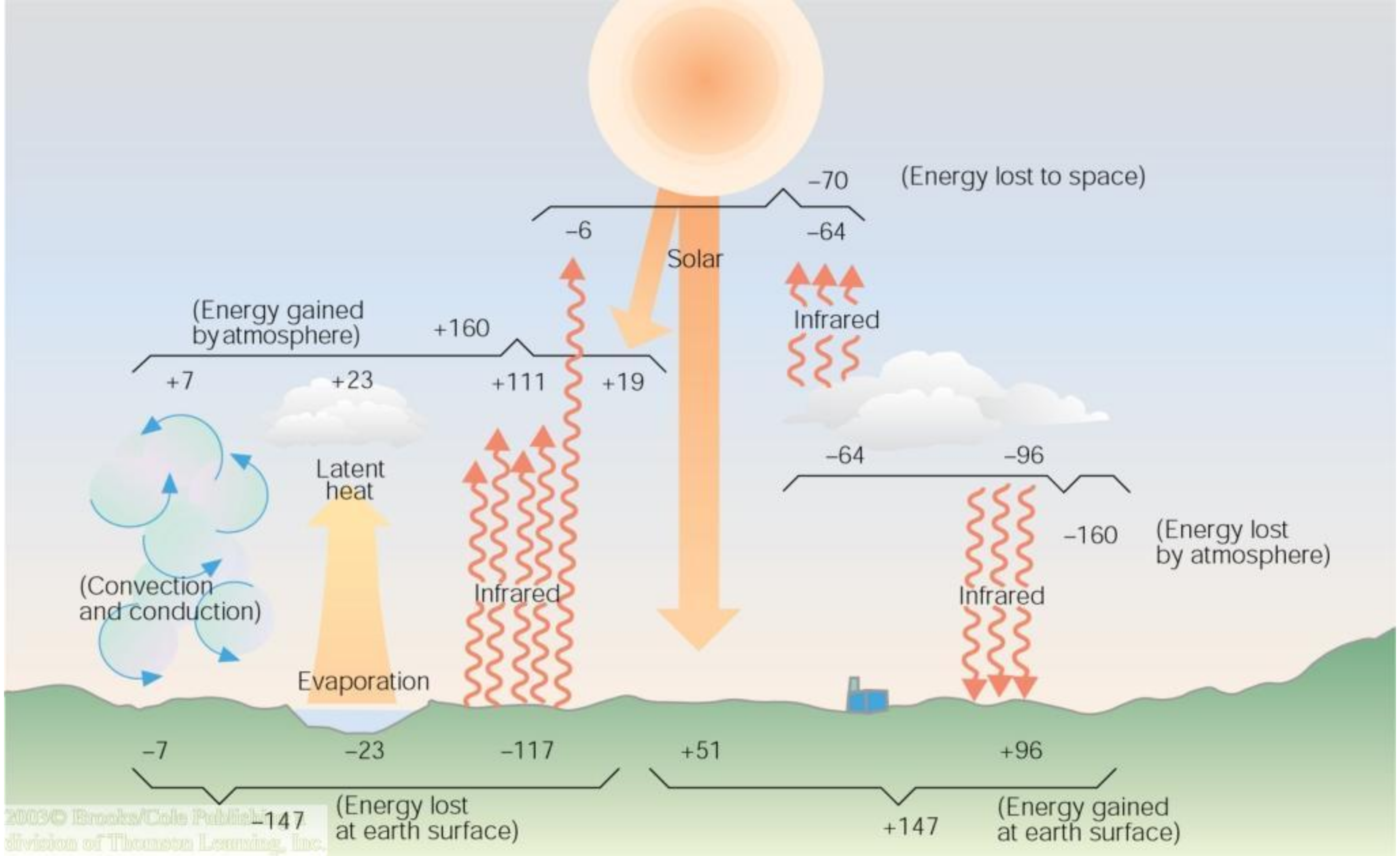


Incoming Solar Radiation



Solar radiation is scattered and reflected by the atmosphere, clouds, and earth's surface, creating an average albedo of 30%. Atmospheric gases and clouds absorb another 19 units, leaving 51 units of shortwave absorbed by the earth's surface.

Earth-Atmosphere Energy Balance



Earth's surface absorbs the 51 units of shortwave and 96 more of longwave energy units from atmospheric gases and clouds.

These 147 units gained by earth are due to shortwave and longwave greenhouse gas absorption and emittance.

Earth's surface loses these 147 units through conduction, evaporation, and radiation.

Absorption & Emission

Solar radiation is selectively absorbed by earth's surface cover.

Darker objects absorb shortwave and emit longwave with high efficiency.

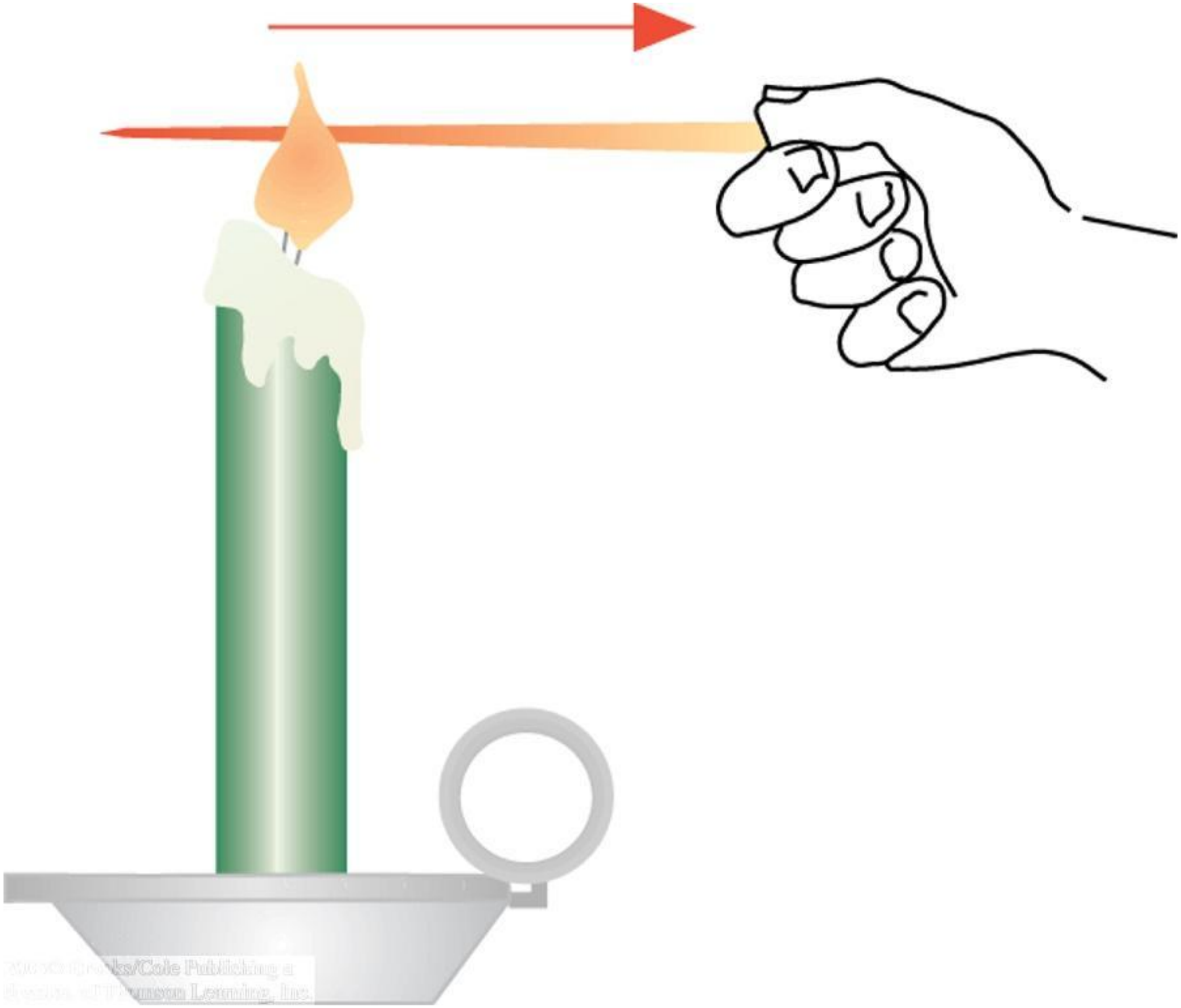
In a forest, this longwave energy melts snow.

Scattered Light

Solar radiation passing through earth's atmosphere is scattered by gases, aerosols, and dust.

At the horizon sunlight passes through more scatterers, leaving longer wavelengths and redder colors revealed.

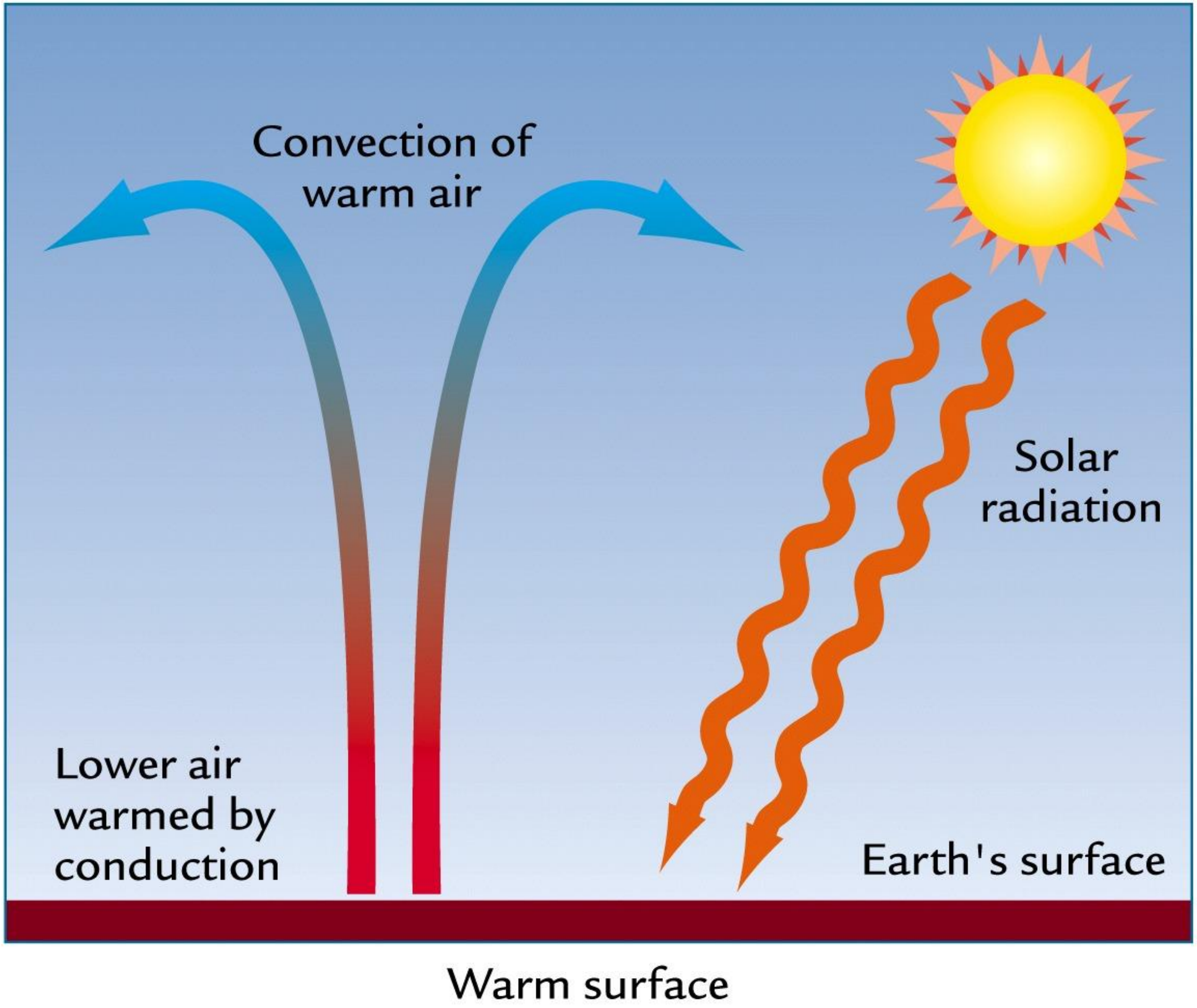
Heat Transfer: Conduction



Conduction of heat energy occurs as warmer molecules transmit vibration, and hence heat, to adjacent cooler molecules.

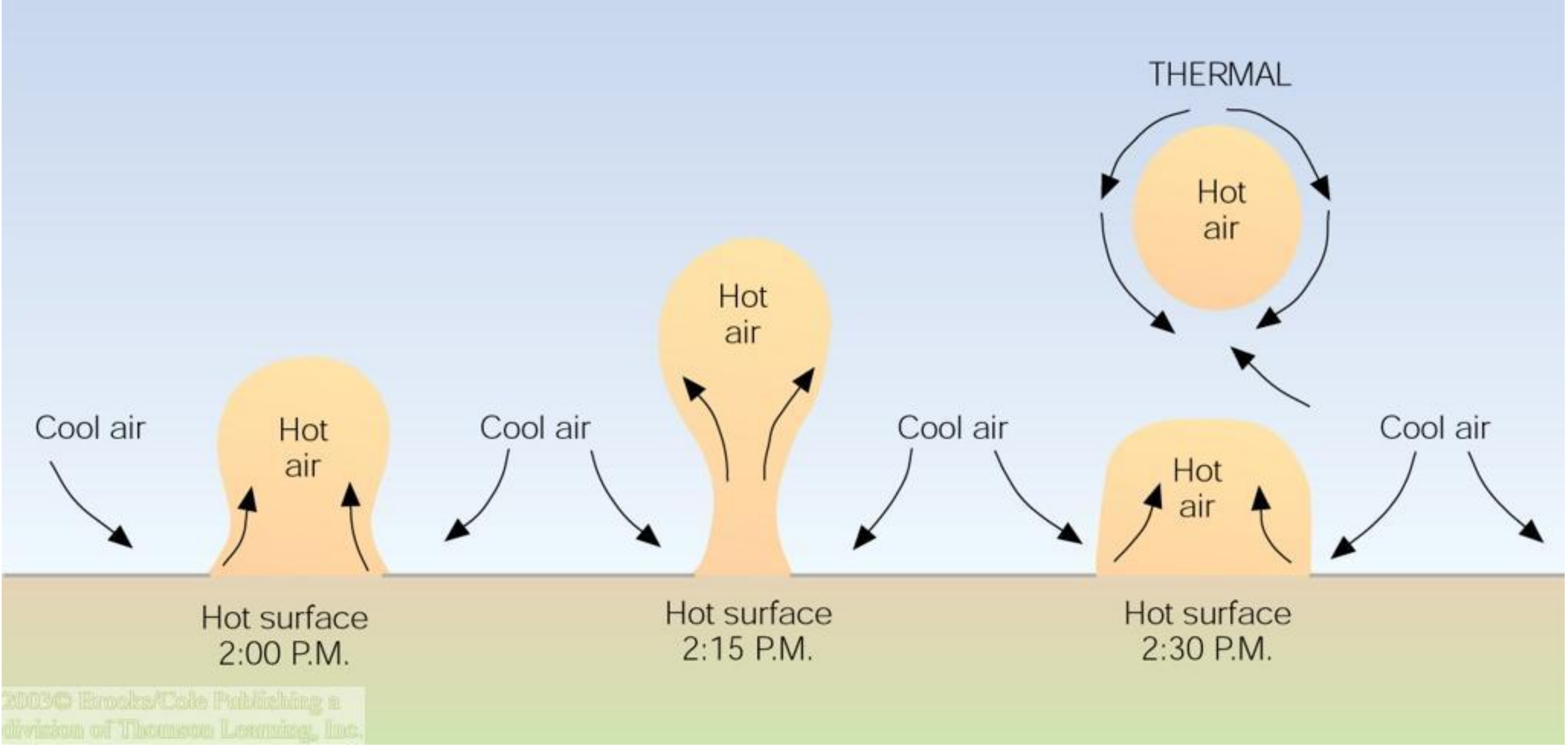
Warm ground surfaces heat overlying air by conduction.

Heat Transfer: Convection of Sensible Heat



Convective turbulence

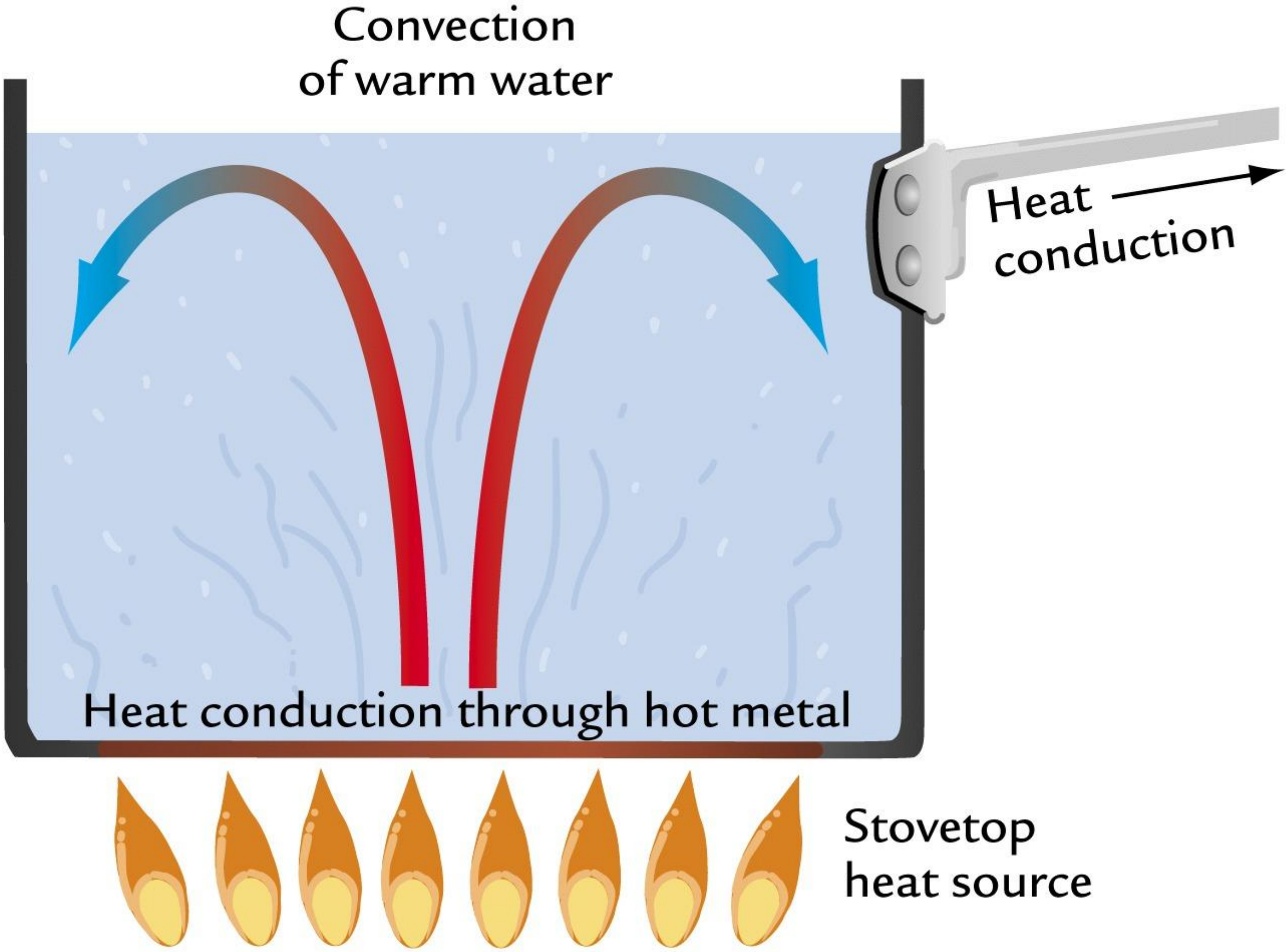
Another Example of Convection



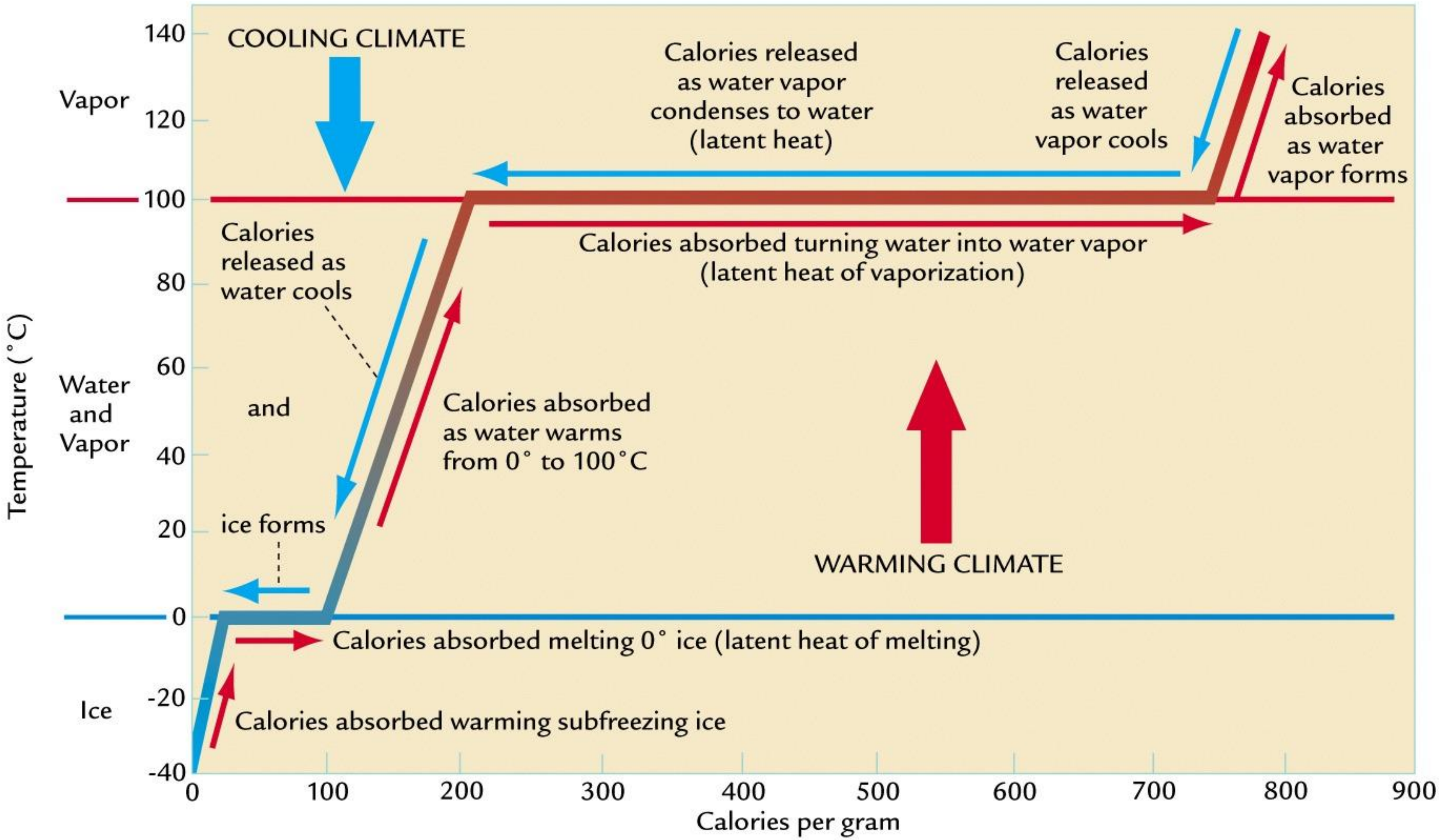
Convection is heat energy moving as a fluid from hotter to cooler areas.

Warm air at the ground surface rises as a thermal bubble expands, consumes energy, and hence cools.

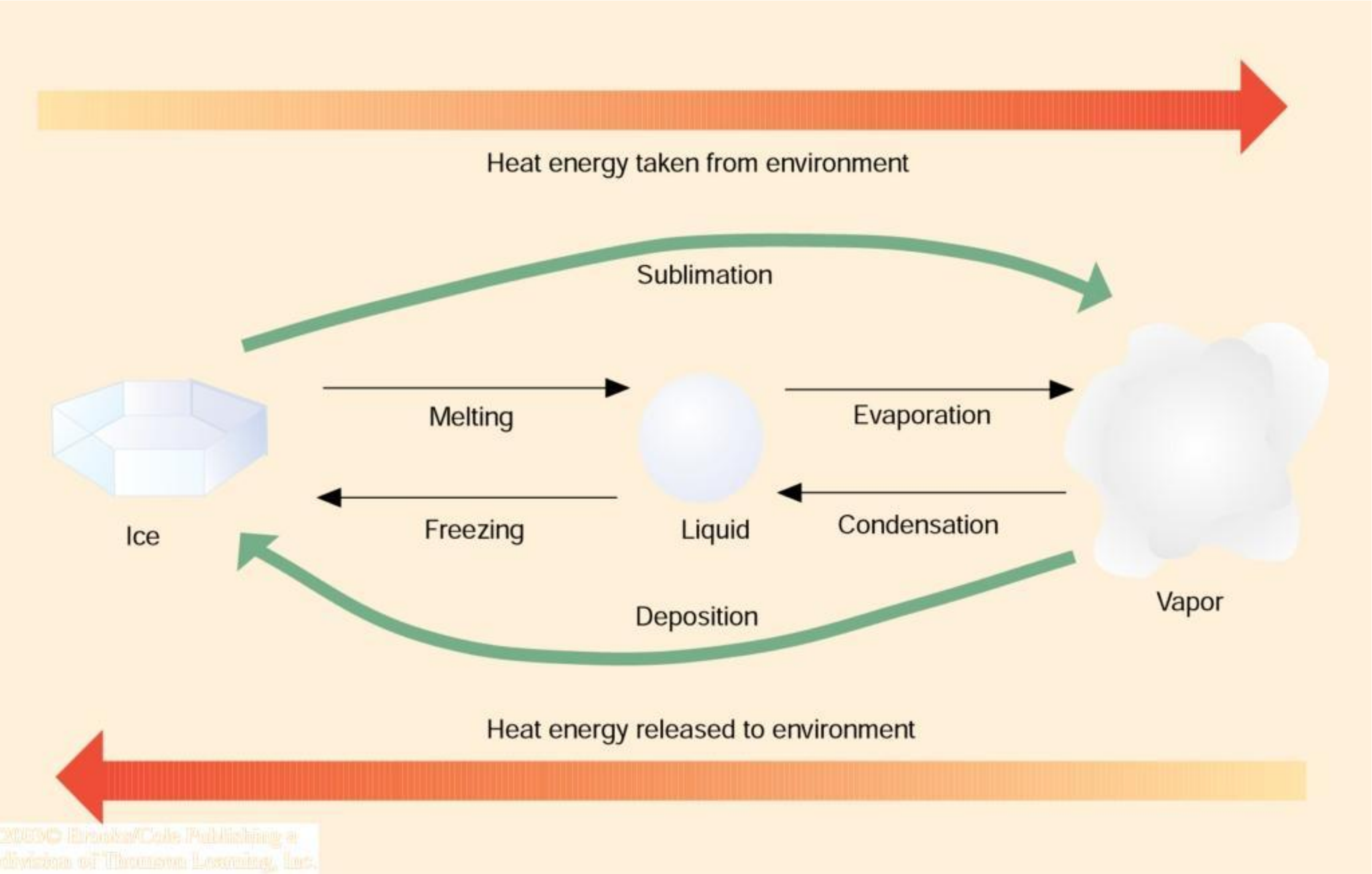
Convection: A Household Example



Heat Transfer: Latent Heat



Latent Heat

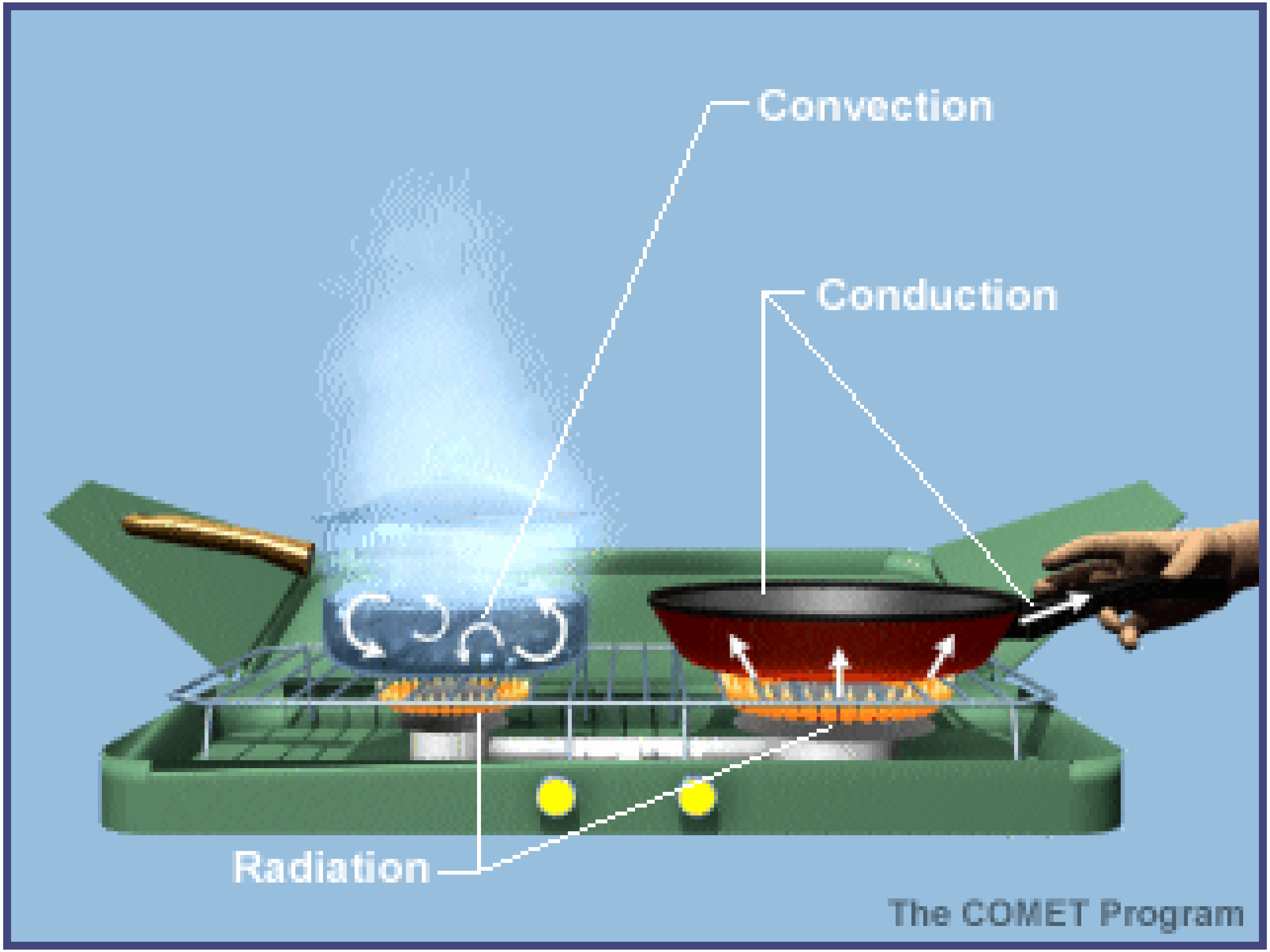


As water moves toward vapor it absorbs latent (e.g. not sensed) heat to keep the molecules in rapid motion.

Heat Energy for Storms

Latent heat released from the billions of vapor droplets during condensation and cloud formation fuels storm energy needs, warms the air, and encourages taller cloud growth.

Radiation, Convection and Conduction



Basic Energy and Mass Transfers in the Atmosphere

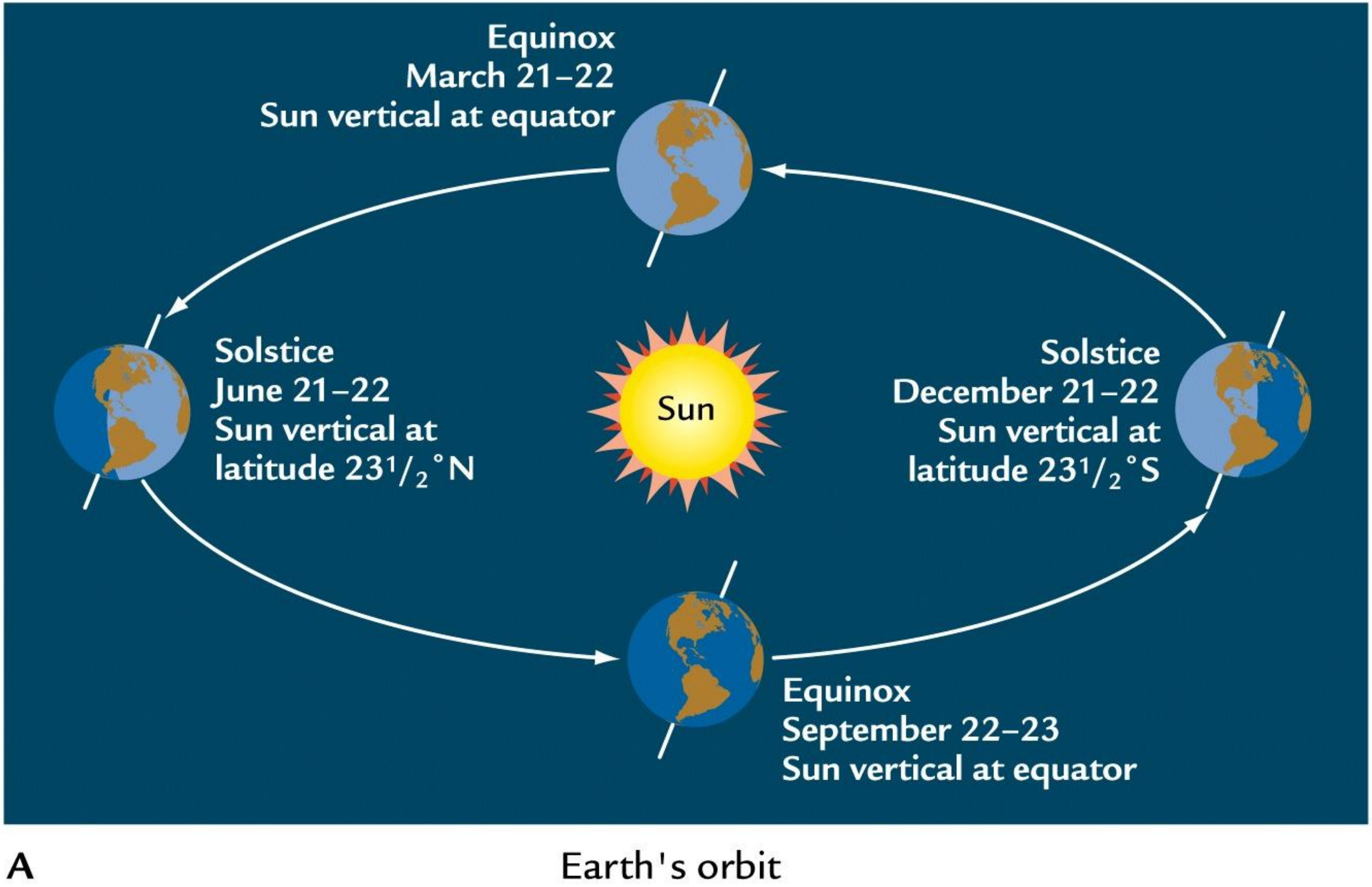
- Processes transfer heat/mass between the Earth’s surface and the atmosphere
  - Radiation
  - Conduction
  - Convection
  - Turbulence

- Three processes affect radiation in the Earth’s atmosphere and the forested environment
  - Absorption
  - Scattering
  - Reflectance

Basic Energy and Mass Transfers in the Atmosphere (Cont’d)

- Processes transfer heat/mass between the Earth’s surface and the atmosphere
  - **Radiation:** the transfer of heat energy without the involvement of a physical substance in the transmission. Radiation can transmit heat through a vacuum.
  - **Convection:** transmits heat by transporting groups of molecules from place to place within a substance. Convection occurs in fluids such as water and air, which move freely.
  - **Turbulence:** is the tendency for flow conditions to be chaotic or stochastic.
  - **Conduction** is the process by which heat energy is transmitted through contact with neighboring molecules.

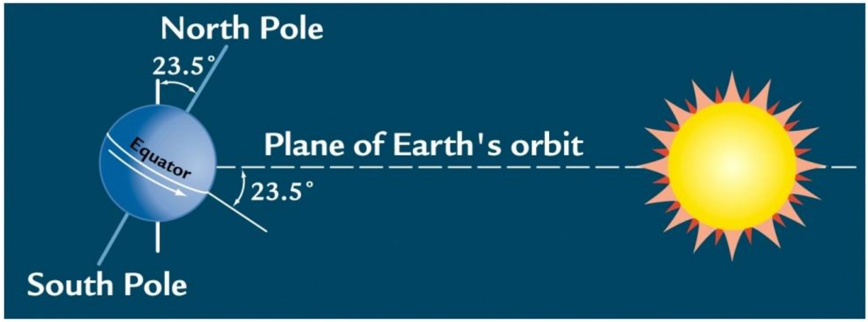
Why do we have seasons?



Earth's orbit

Earth’s Tilt and Seasonal Radiation

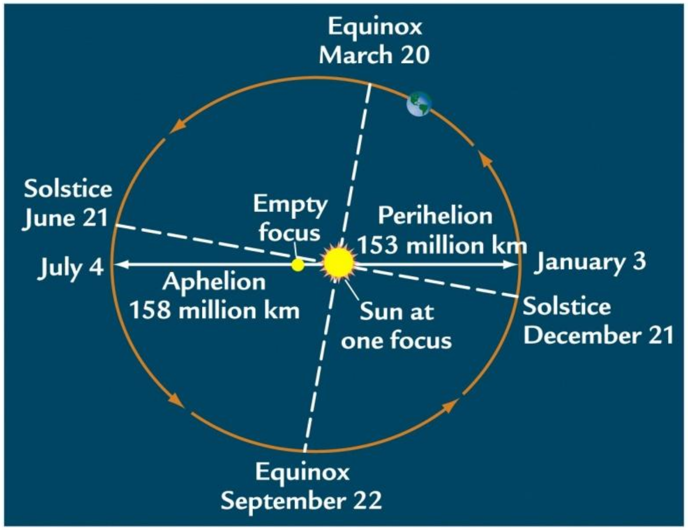
Earth's Orbit Today and the Seasons



- Orbit around Sun: slightly elliptical

- Tilt of spin axis at 23.5°

  Rotation on axis (day&night) in 24 hrs
  Speed (eq 1038 mi/hr, 0 at axis)
  Axis points toward North Star (Polaris)



- Summer Solstice (NH) on June 21/22

  Axis toward Sun
  Vertical rays on Tropic of Cancer (23.5°N Lat)
  24-hr day above Arctic Circle (66.5°N Lat)
  24-hr night below Antarctic Circle (66.5°S Lat)

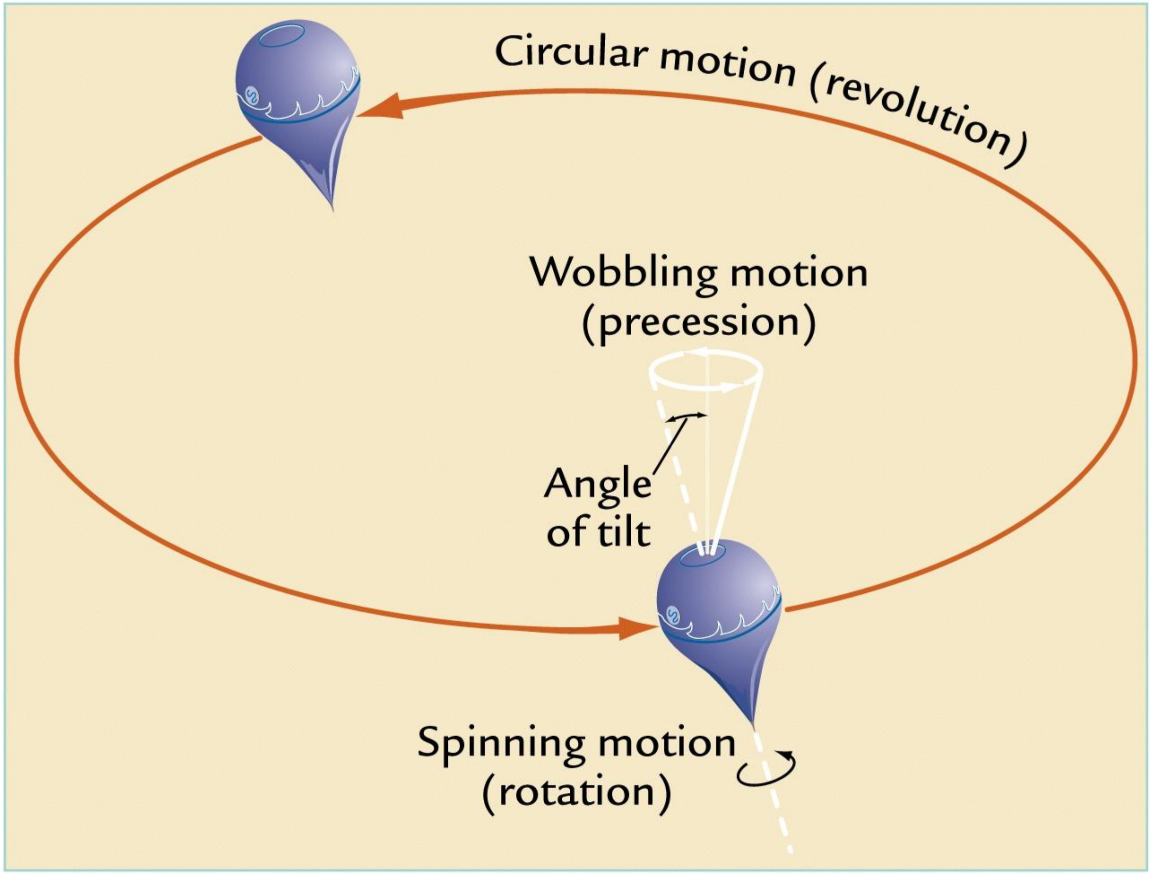
- Winter Solstice (NH) on Dec. 21/22

  Axis away from Sun
  Vertical rays on Tropic of Capricorn (23.5°S Lat)
  24-hr night above Arctic Circle (66.5°N Lat)
  24-hr day below Antarctic Circle (66.5°S Lat)

- Fall Equinox (NH) on Sept 22/23 (day = night length at all points)

- Spring Equinox (NH) on March 20/21
  (day=night length at all points)

Earth’s Orbit Parameters

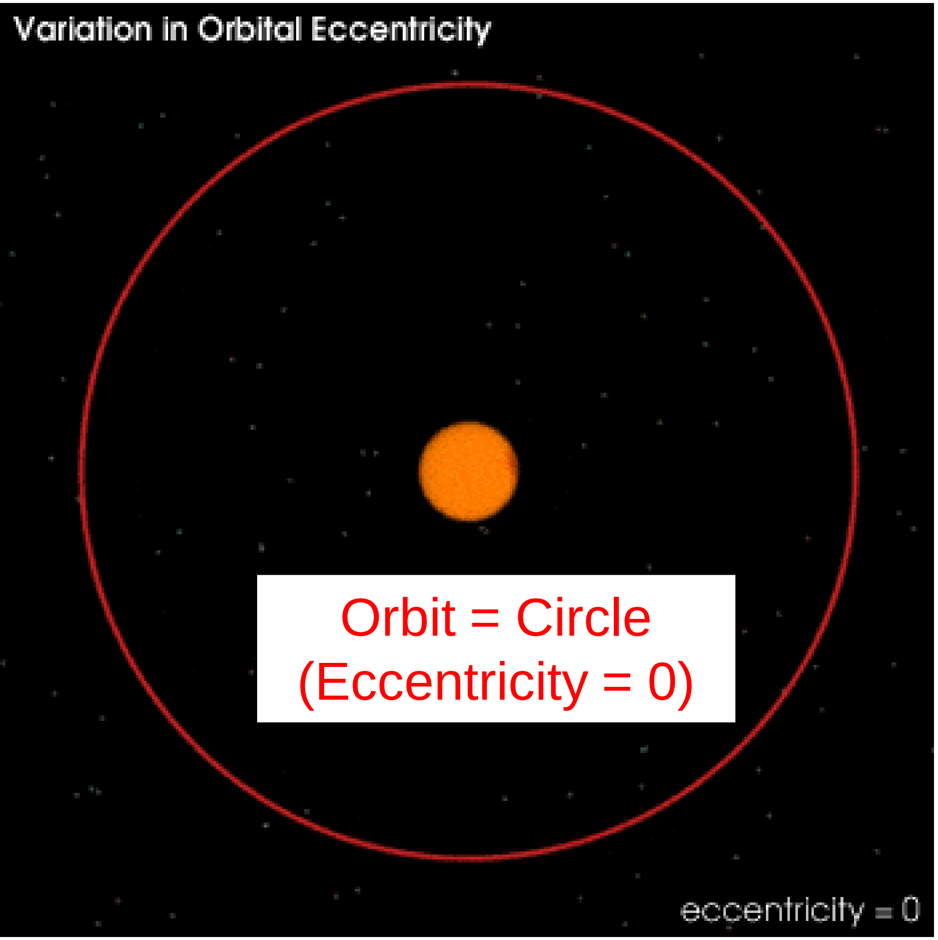


Eccentricity (shape of the orbit: varies from being elliptical to almost circular)

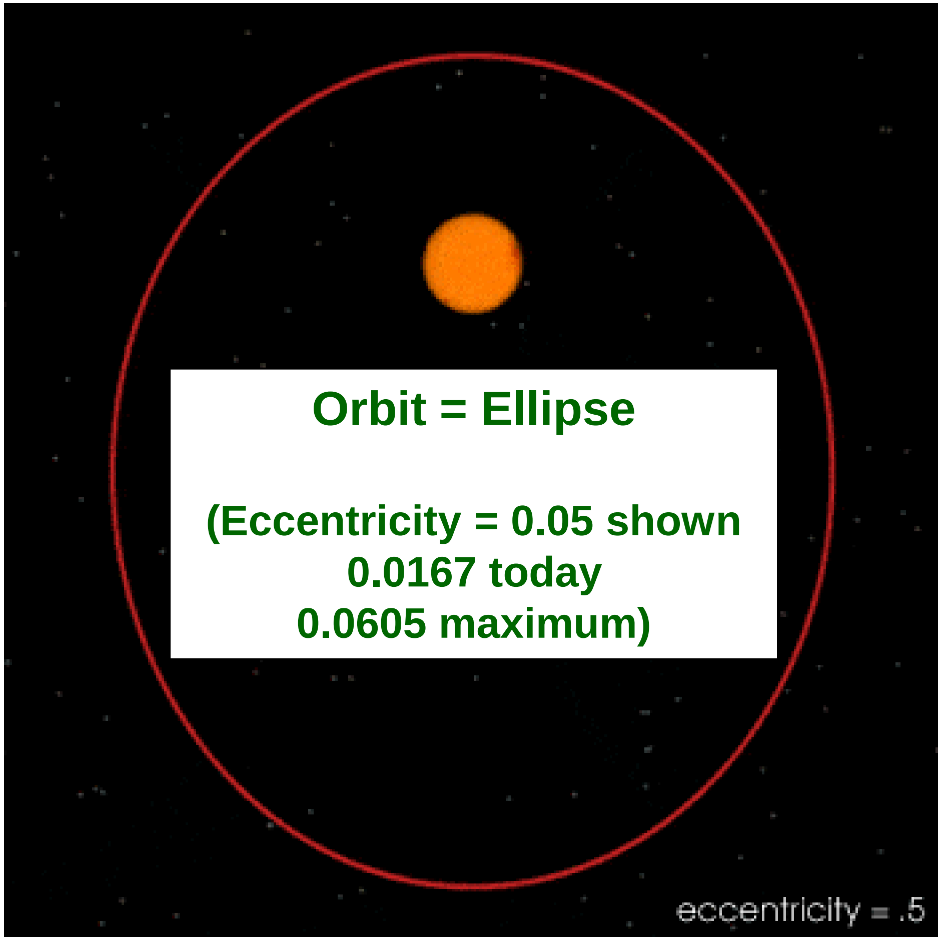
Obliquity (tilt of the axis of rotation)

Precession (wobbling of the axis of rotation)

Eccentricity: Earth’s orbit around the sun



Orbit = Circle
(Eccentricity = 0)

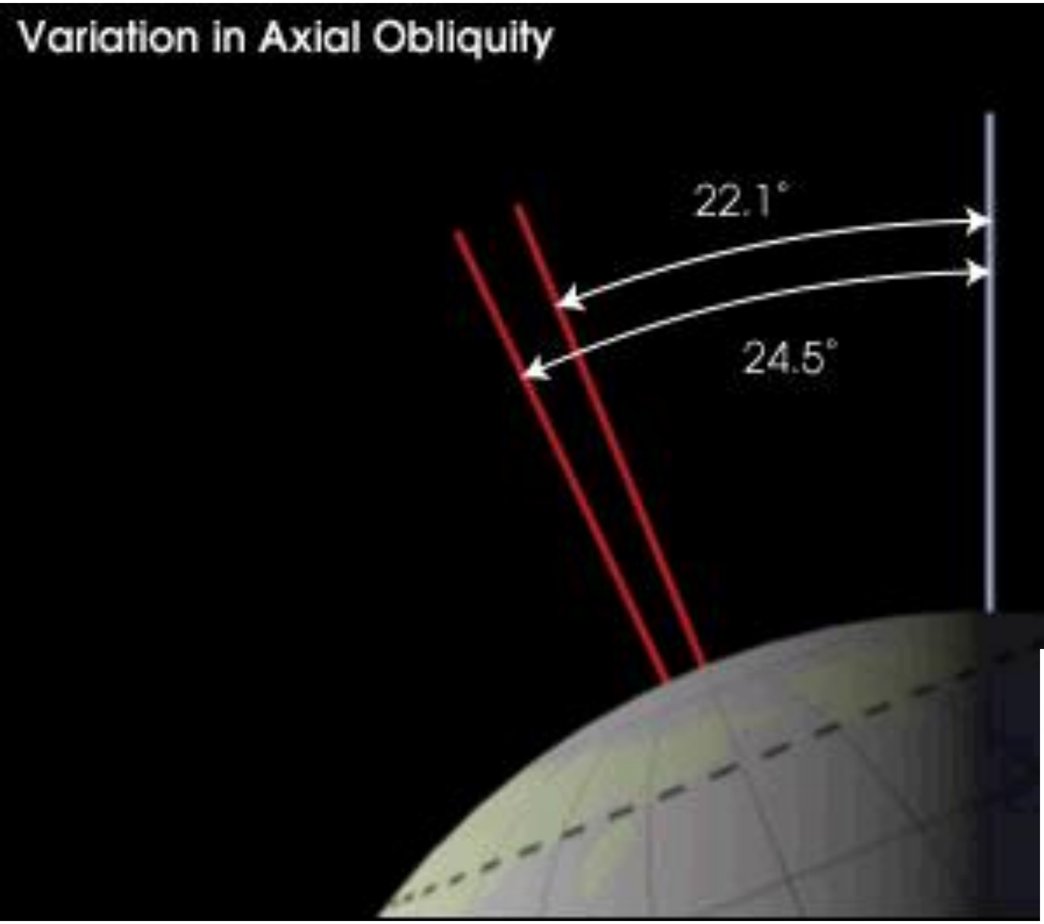


Orbit = Ellipse

**(Eccentricity = 0.05 shown
0.0167 today
0.0605 maximum)**

Varies from near circle to ellipse with a period of 100,000 years
Distance to Sun changes → insolation changes

Obliquity: Tilt of the Earth’s rotational axis

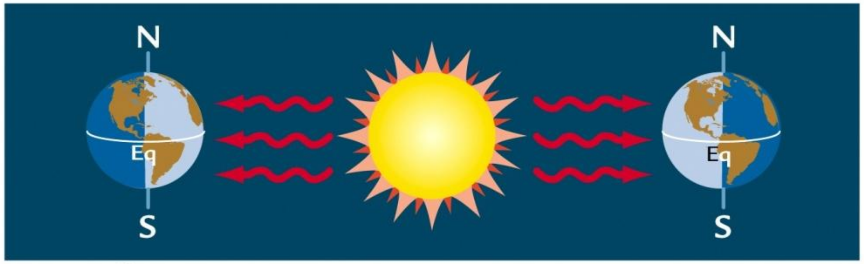


- Cycle of ~ 41,000 years
- Varies from 22.2 to 24.5°

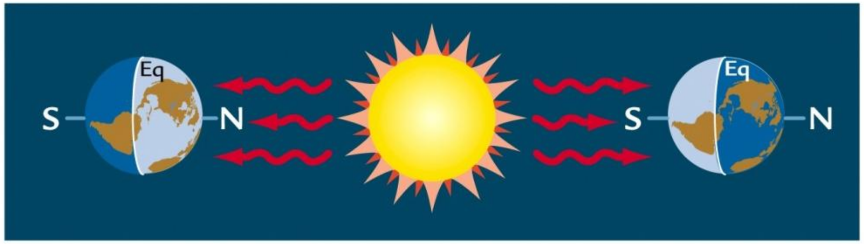
(The current axial tilt is 23.5°)

- Greater tilt = more intense seasons

If Earth’s orbit were circular,
No tilt = no seasons
90° tilt = largest seasonal differences at the poles (6 mon. darkness, 6 mon. overhead sun)

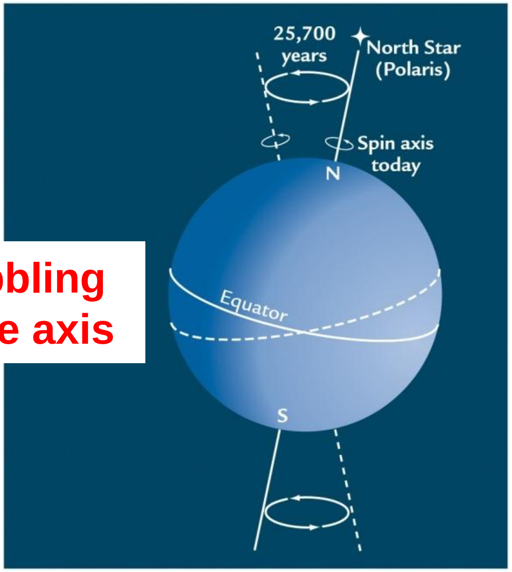


A No tilt

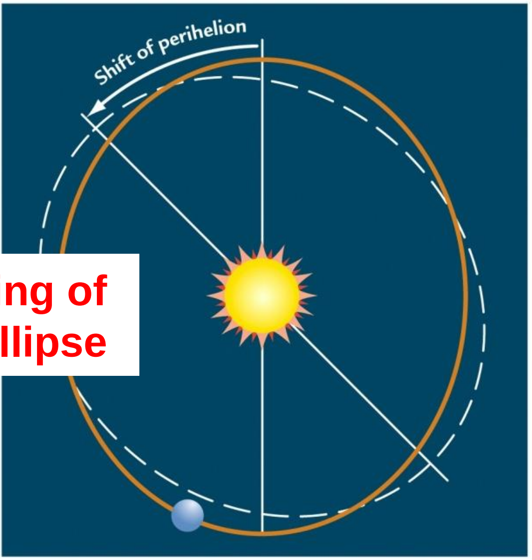


B 90° tilt

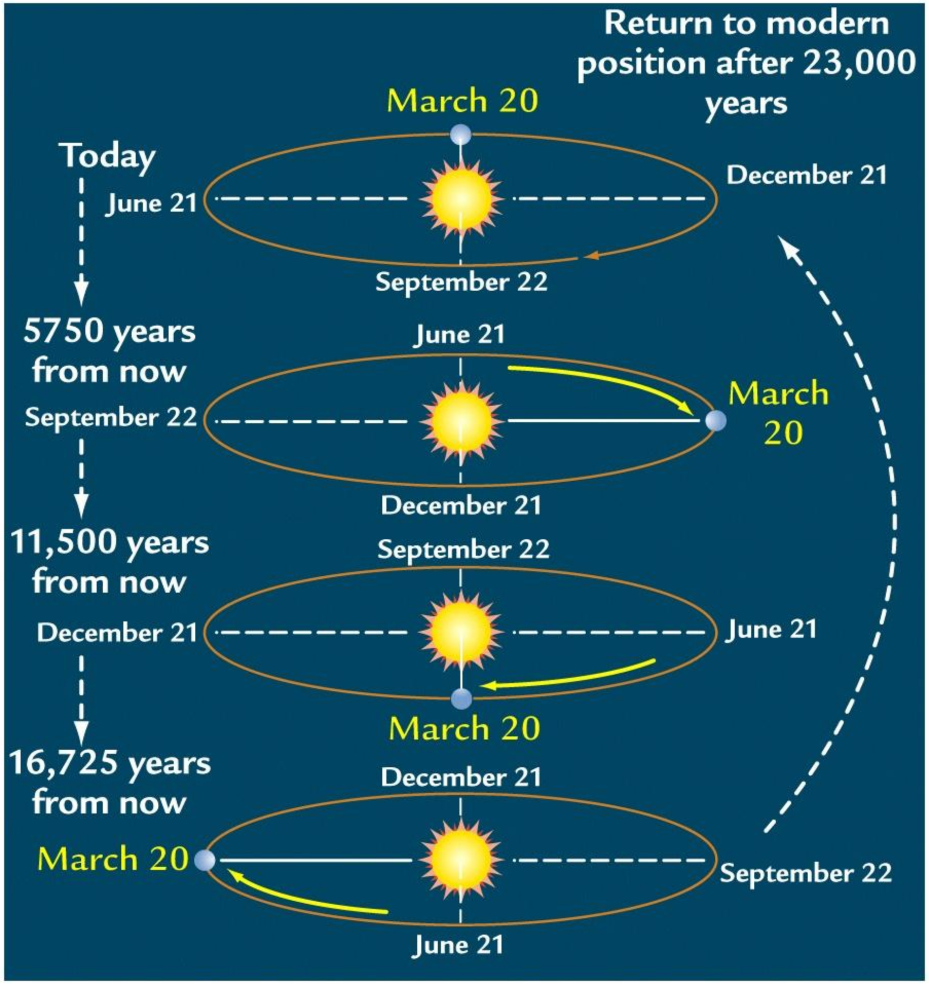
Precession: positions of solstices and equinoxes in the eccentric orbit slowly change



Wobbling of the axis

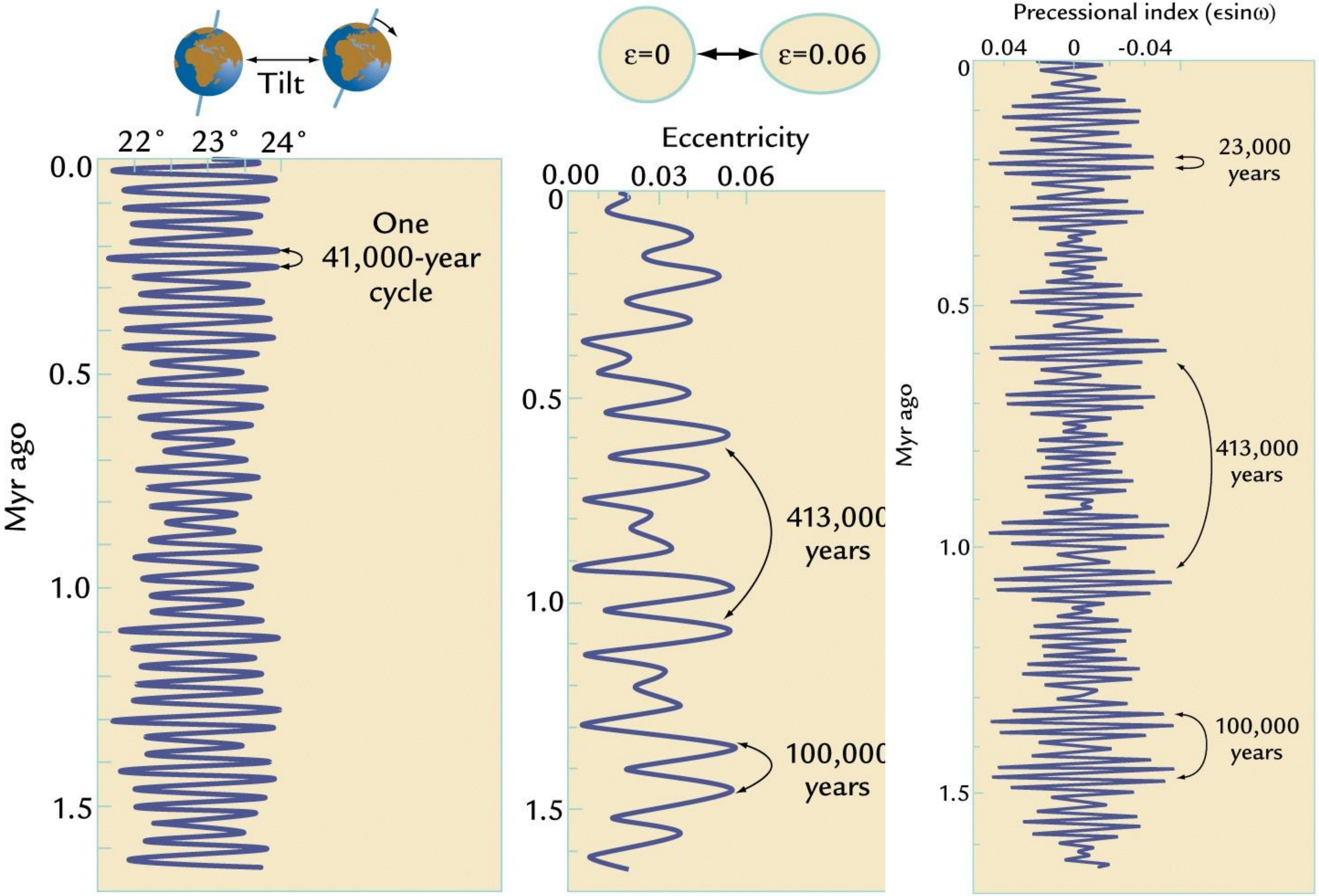


Turning of the ellipse



Period of about 23,000 years

Earth’s Orbit Changes Through Time



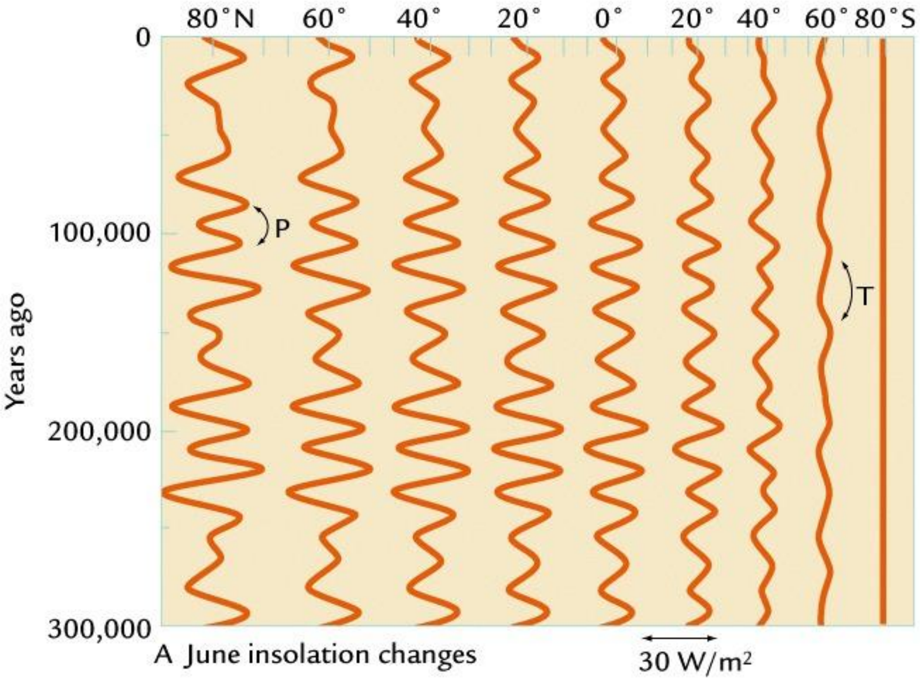
Changes in Insolation Received on Earth

- Precession dominates at low and middle latitudes

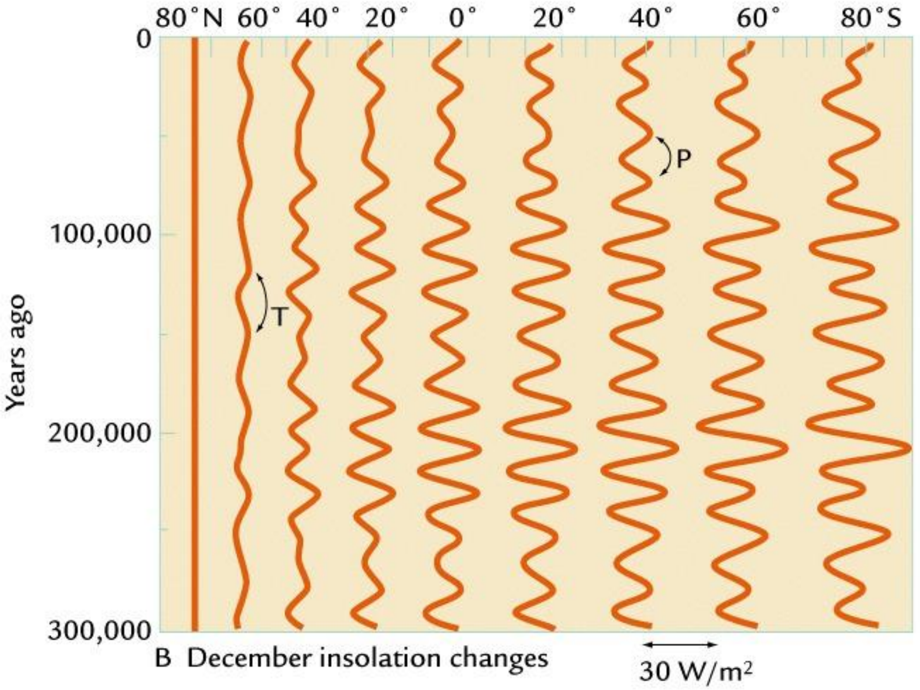
- Tilt is more evident at higher mid-latitudes.

- Eccentricity is not significant directly, but modulates the amplitude of the precession cycle.

- Summer changes dominate over winter at polar latitudes.



A June insolation changes



B December insolation changes