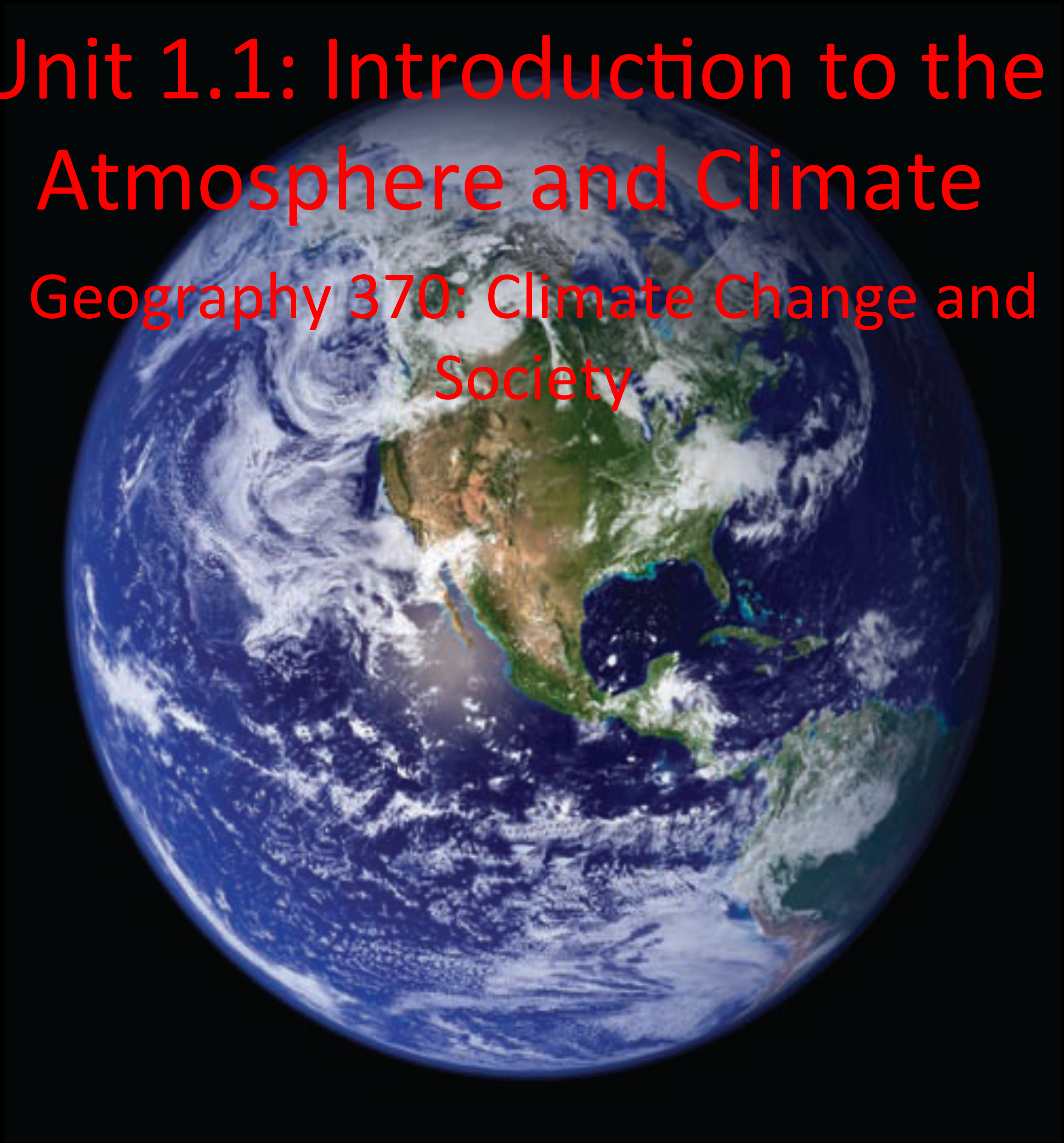
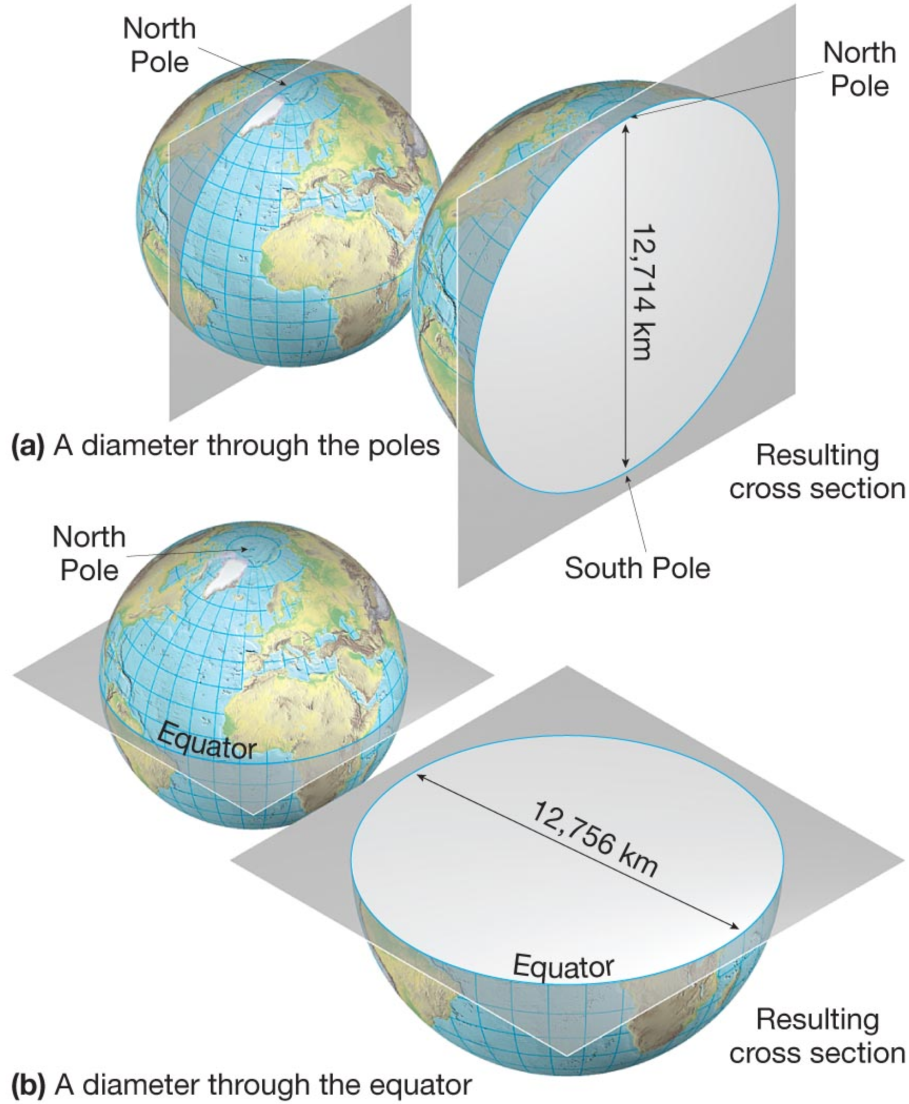
Unit 1.1: Introduction to the Atmosphere and Climate

Geography 370: Climate Change and Society



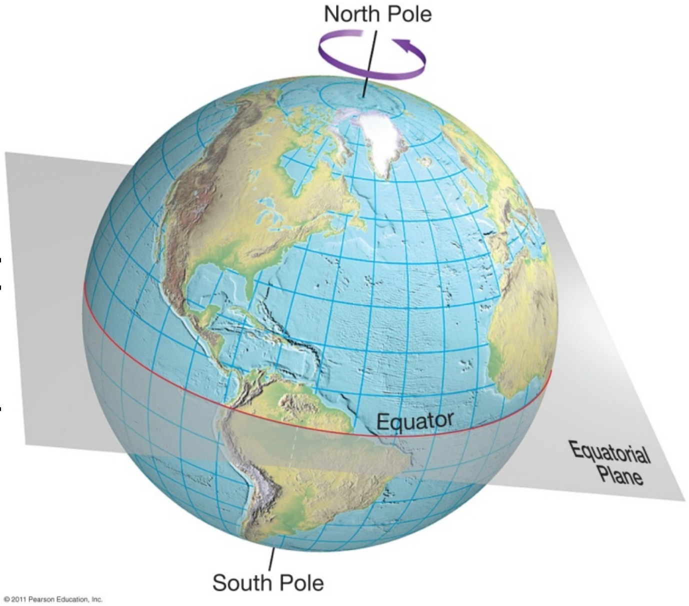
The Size and Shape of the Earth

- **The earth is not flat**
- But it is not a perfect sphere either
- Earth is almost spherical
- It is a bit flattened at the poles and bulges out at the equator
- Because it is not a perfect sphere, there are several ways to approximate earths shape
- This important for mapmakers (cartographers)



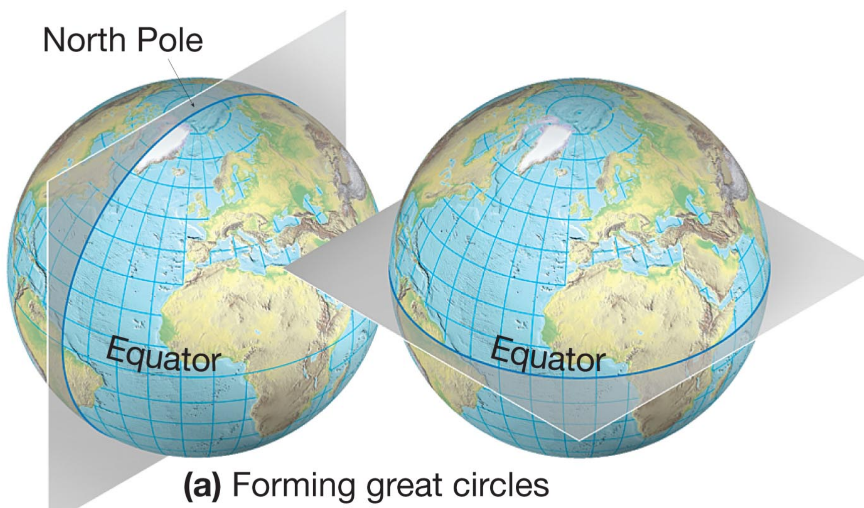
The Geographic Grid

- **Location on Earth**
  - Need an accurate location on Earth to describe geographic features
  - We create a reference grid that is basec on:
    - Earth's rotation axis to base location on tl surface
    - North Pole and South Pole
    - Plane of the Equator—halfway between poles and perpendicular to Earth's surface
  - The geographic grid is characterized by great circles, latitudes and longitudes



The Geographic Grid

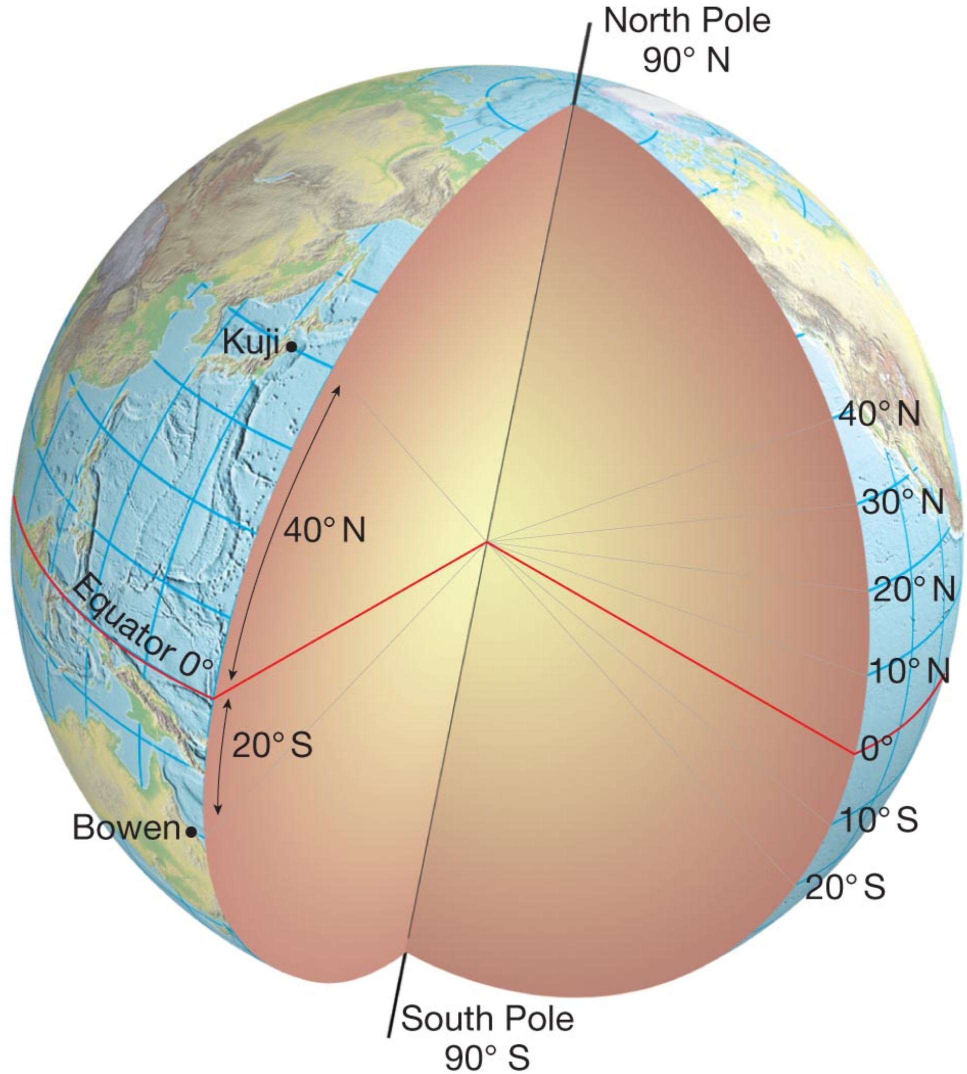
- **Great Circles**
  - Circles which bisect a sphere and pass through the sphere’s center
  - Identify the shortest distance between two points on a sphere—great circle distance



(a) Forming great circles

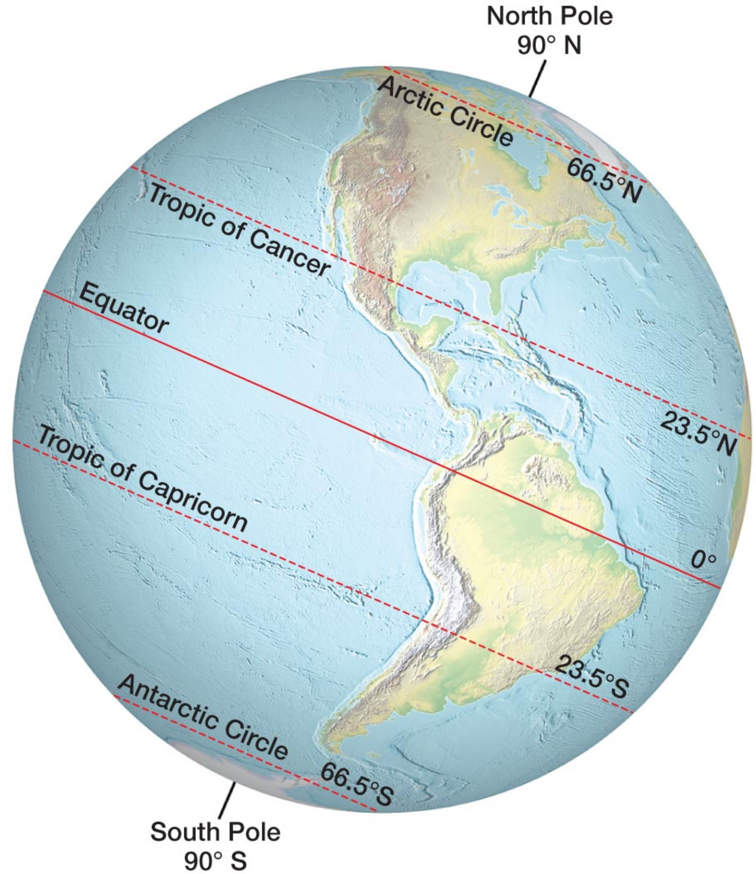
The Geographic Grid

- **Latitudes**
  - angle north or south of the equator
  - Parallels are lines connecting all points at the same latitude



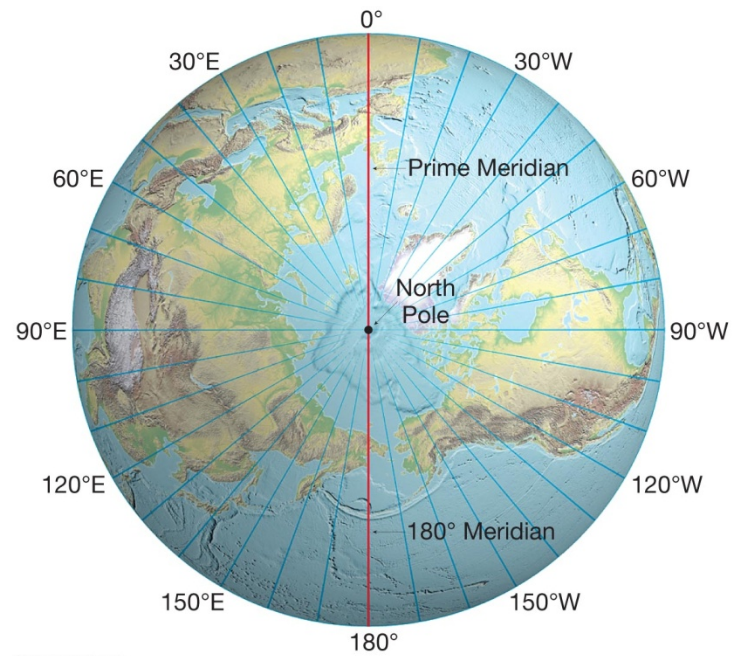
The Geographic Grid

- **Latitudes**
  - 7 important latitudes:
    - Tropic of Cancer and Capricorn (23.5° N and S)
    - Equator (0°)
    - Poles (90° N and S)
    - Arctic and Antarctic Circles (66.5° N and S)
  - Why are they important?
  - Latitudional zones: tropics, midlatitudes, polar etc.



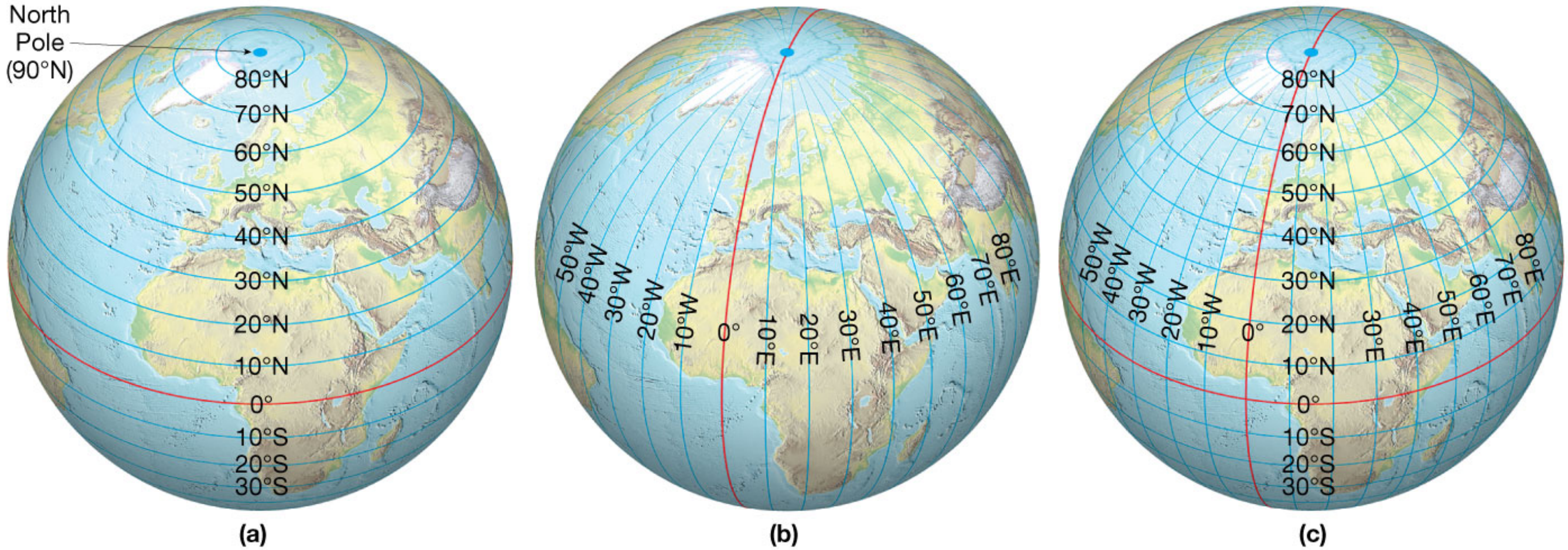
The Geographic Grid

- **Longitudes**
  - The lines connecting all "points" along a longitude is called meridians
  - Prime Meridian (0° longitude) located at Greenwich, England
  - angle east or west of the Prime Meridian
  - Converge at the poles



The Geographic Grid

- The network of parallels and meridians create a geographic grid
- Any point on earth can be referenced with latitude and longitude coordinates
- Degrees of latitude and longitude are divisible into minutes (1/60 of a degree) and seconds (1/60 of a minute). Decimal divisions are now more common.
- Example with Google Earth.

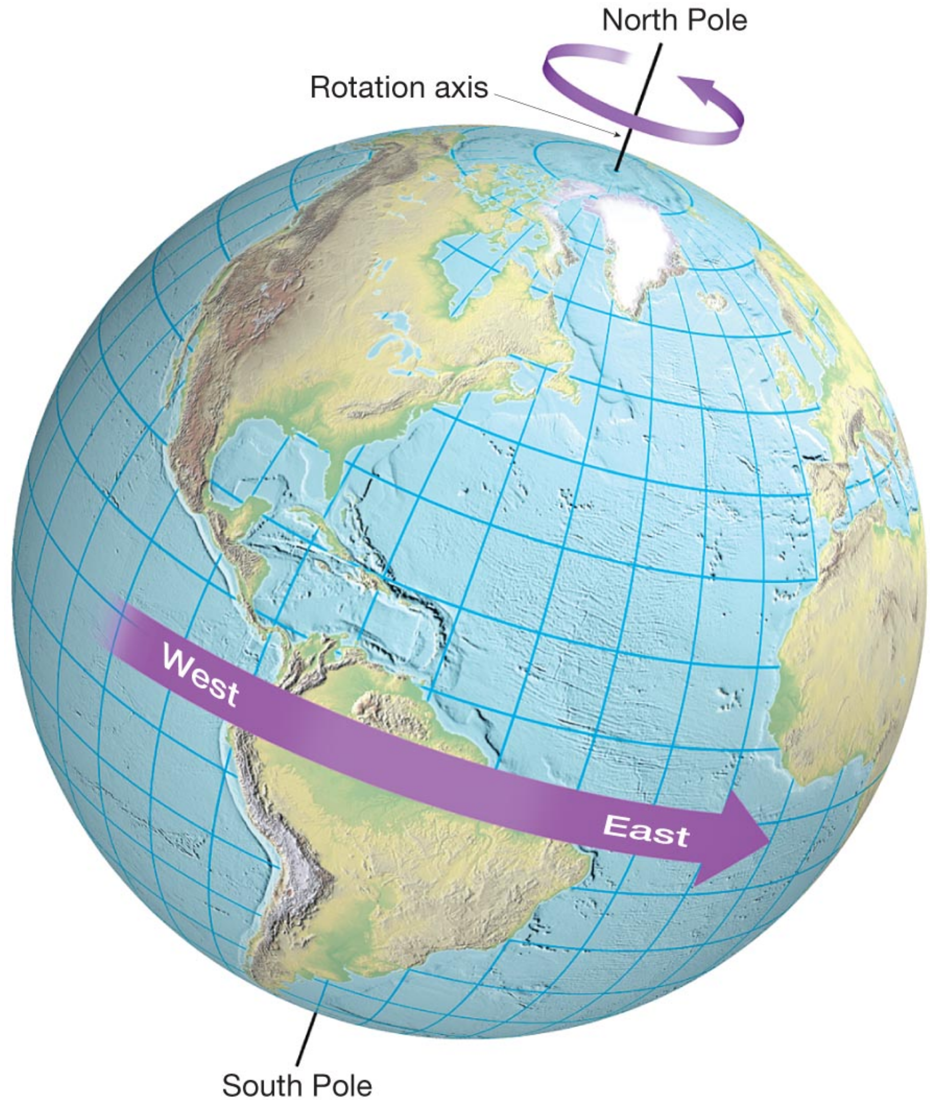


Earth-Sun Relations

- **The Sun has a profound impact on the energy, weather and life of planet Earth**
- For example, the revolution of the Earth around the sun explains the seasons and the rotation of the Earth on its axis explain day and night
- http://www.rkm.com.au/animations/animation-seasons.html

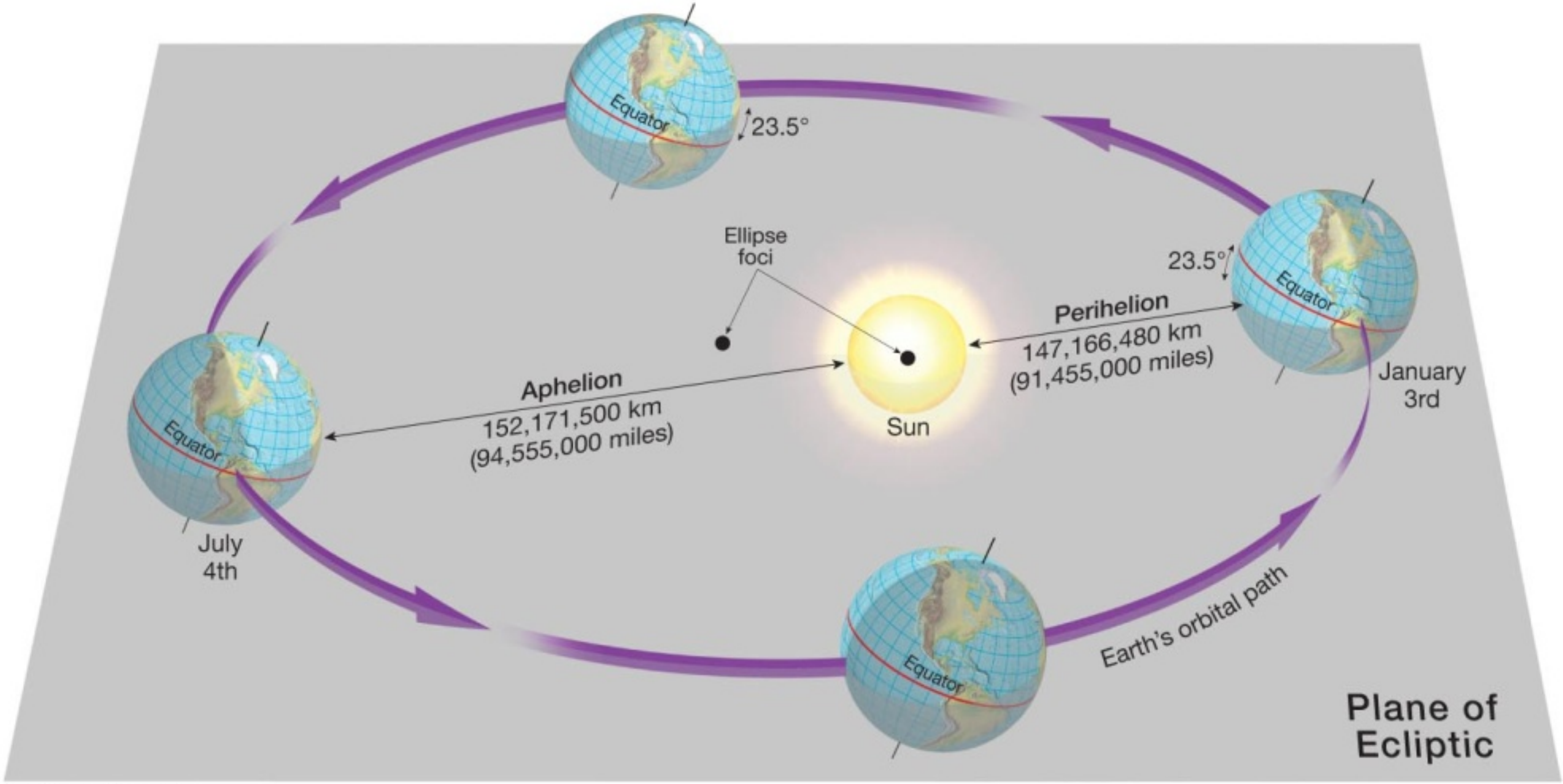
Earth-Sun Relations

- **Rotation of the Earth**
  - 24 hours for one rotation
  - Diurnal transition from light to darkness with huge impact on all life
  - Explains flow direction of wind and ocean current
  - Tidal effects from the Moon and Sun



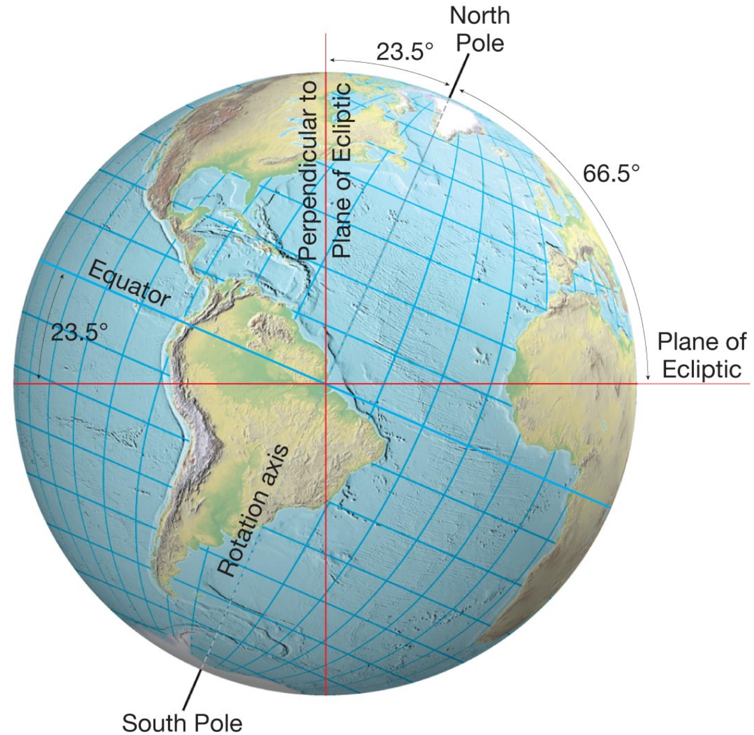
Earth-Sun Relations

- **Earth's Revolution around Sun**
  - One revolution takes 365 ¼ days



Earth-Sun Relations

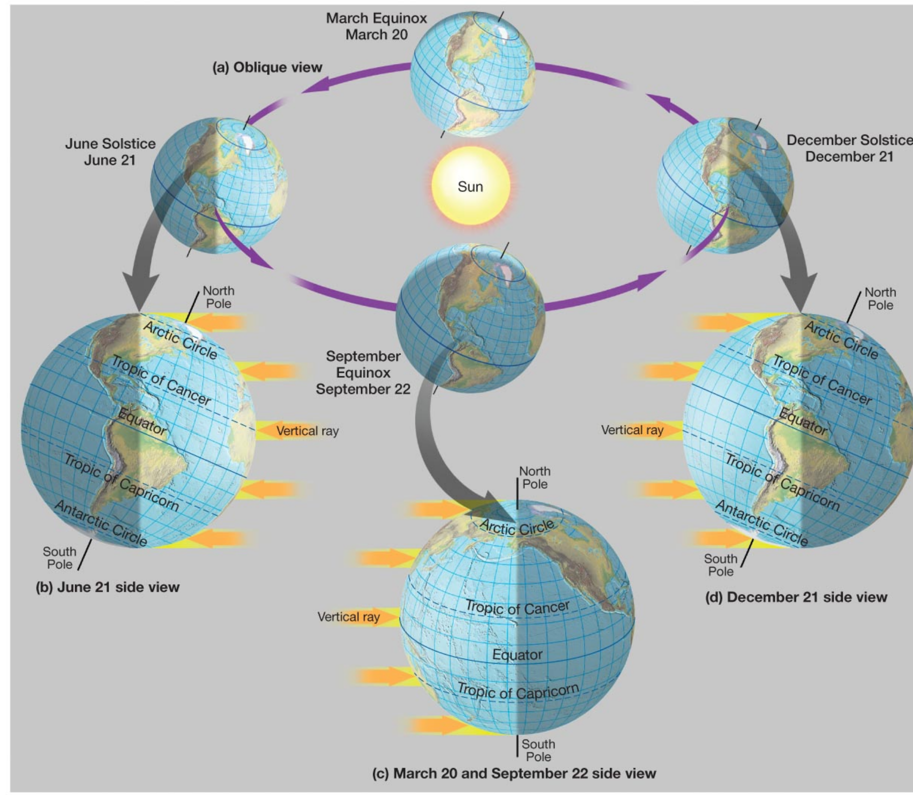
- **Orbital Properties**
  - Plane of the Earth's orbit is the plane of the ecliptic
  - Earth's axis tilted at 23.5°
  - Plane of ecliptic is not parallel



- The tilt of the earth and the rotation of earth results in earth seasonal patterns

The Annual March of the Seasons

- The change of seasons are linked to four special days
- Two solstices
  - June solstice
  - December solstice
- Two equinoxes
  - March equinox
  - September equinox



The Annual March of the Seasons

- **June solstice**
  - Occurs on approximately June 22 each year
  - Sun is directly overhead at 23.5° N latitude
  - Antarctic Circle in 24 hours of darkness
  - Marks start of summer in Northern Hemisphere; winter in Southern Hemisphere

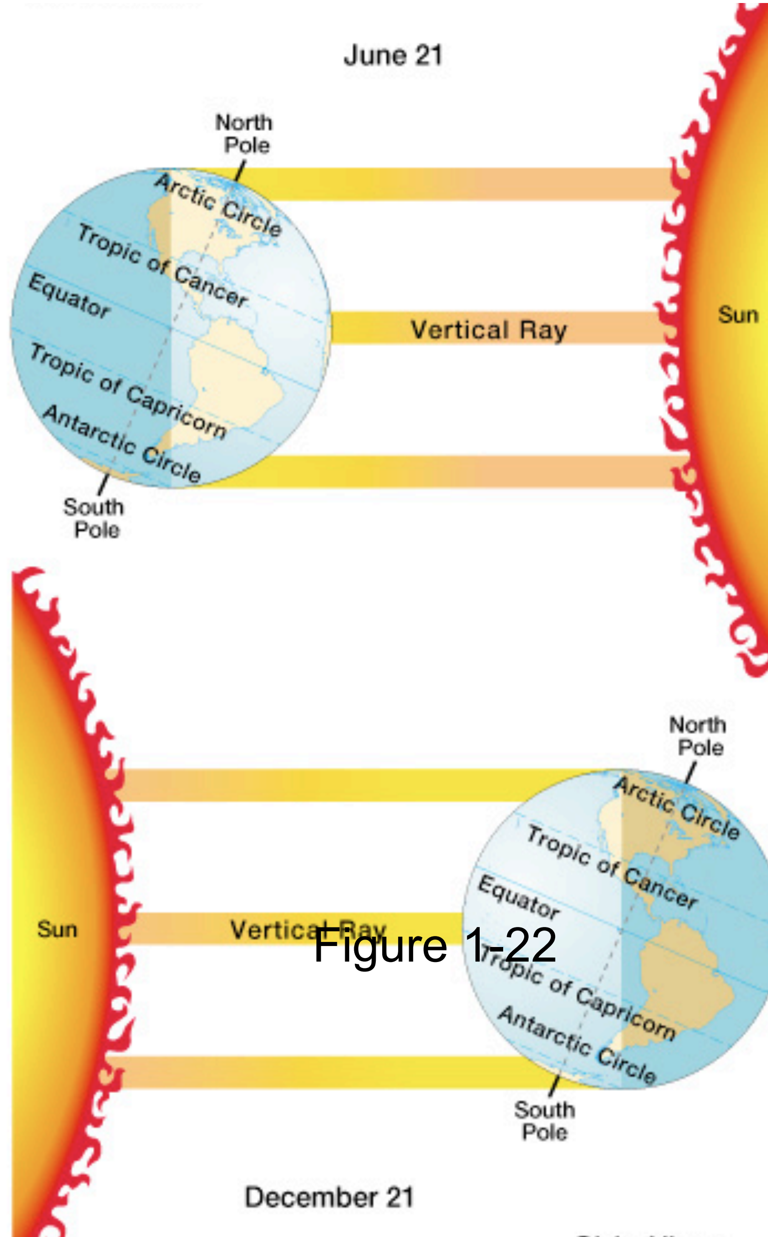
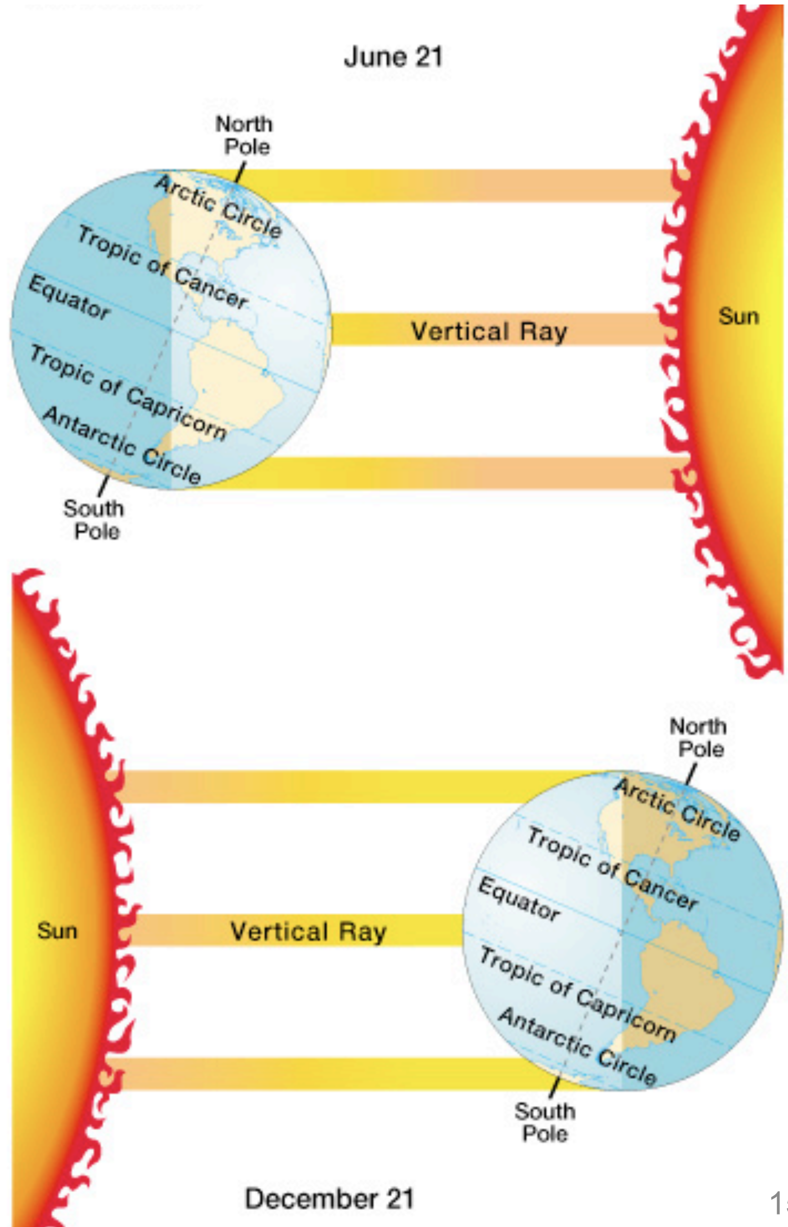


Figure 1-22

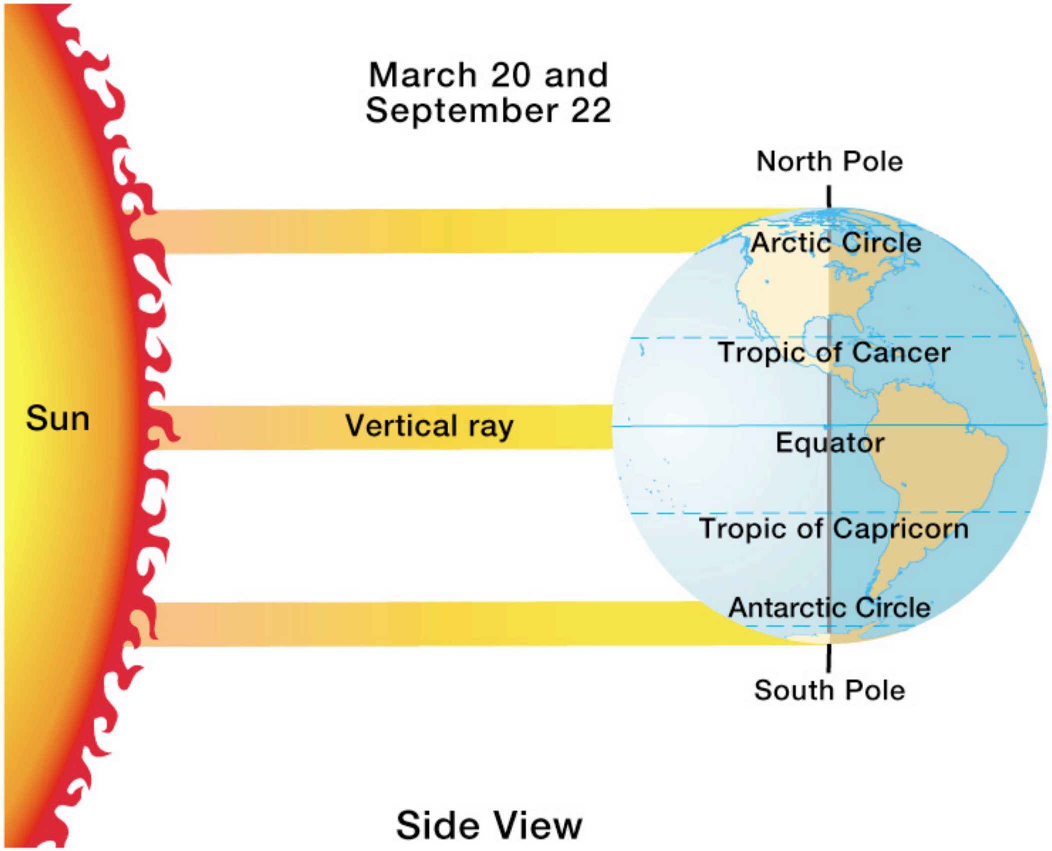
The Annual March of the Seasons

- **December solstice**
  - Occurs on approximately December 22 each year
  - Sun is directly overhead at 23.5° S latitude
  - Arctic Circle in 24 hours of darkness
  - Marks start of winter in Northern Hemisphere; summer in Southern Hemisphere



The Annual March of the Seasons

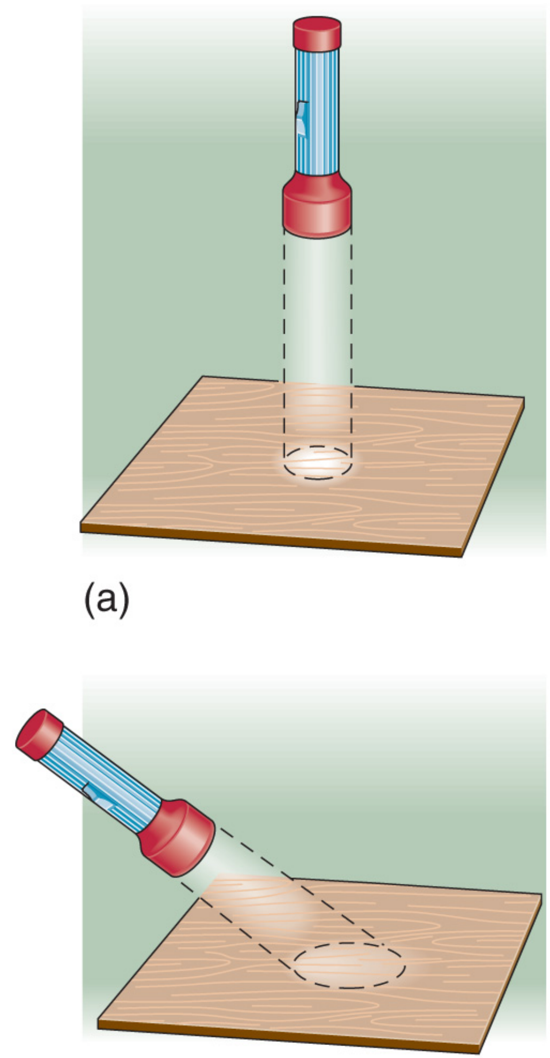
- **Equinoxes**
  - Occur on approximately March 21 and September 21 each year
  - Day length is 12 hours worldwide ("equinox")
  - Sun is directly overhead at the equator



Causes of Earth's Seasons

- Solar Angle

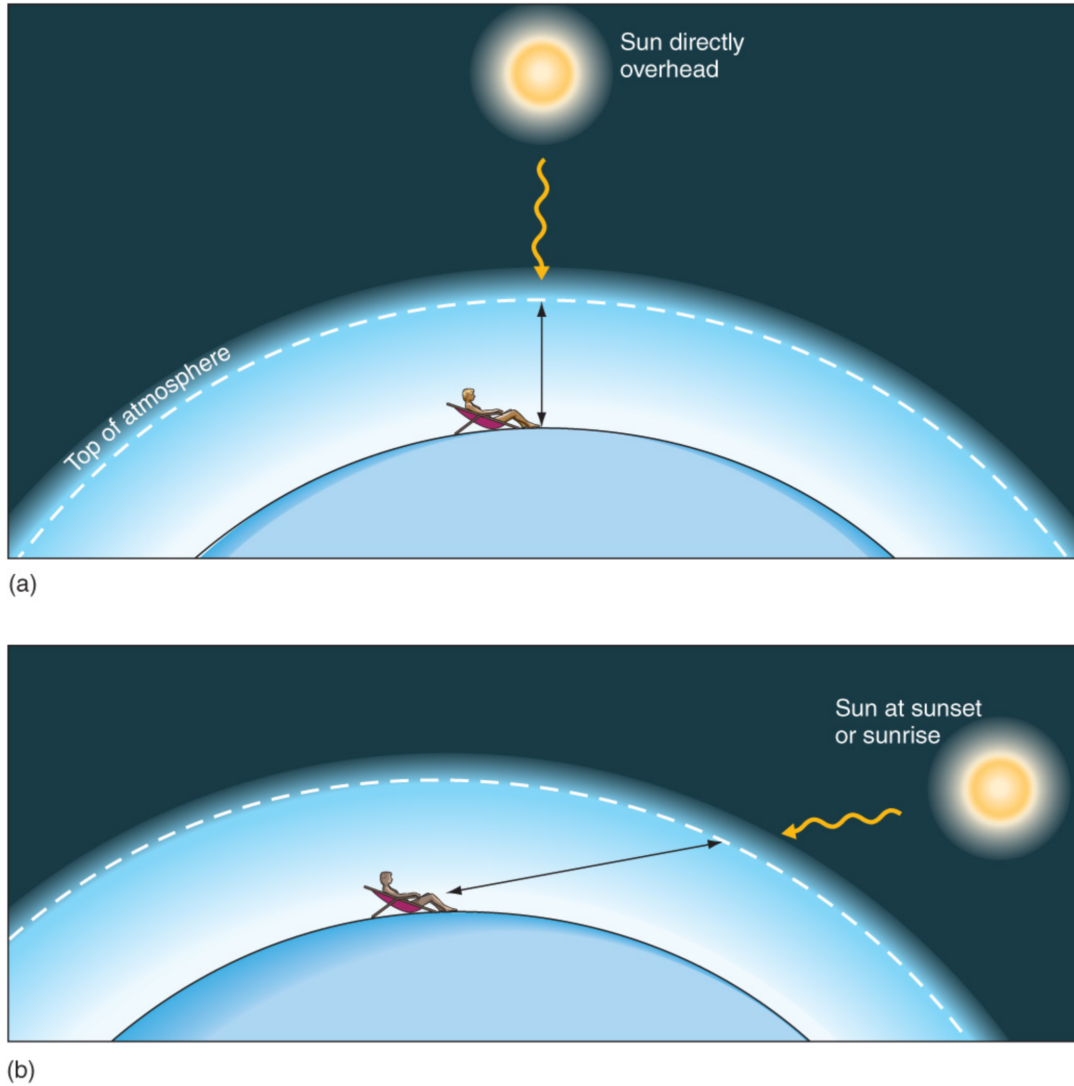
- Solar radiation is directly related to solar angle.
- Higher solar angles reduce **<u>beam spreading,</u>** which leads to warming.
- Lower angles induce less intense warming.



(a)

(b)

Solar Angle

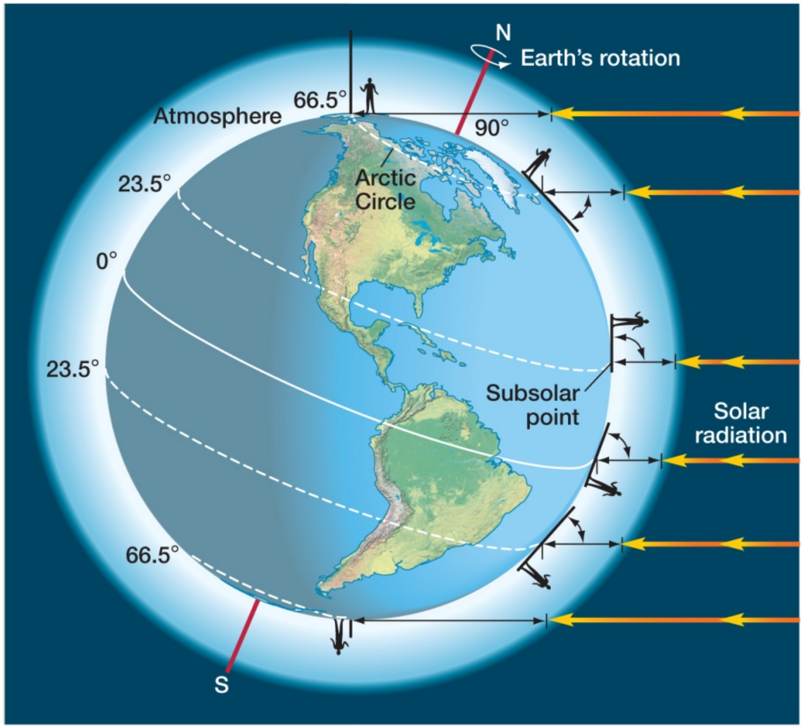

Sun directly overhead
Top of atmosphere
(a)
Sun at sunset or sunrise
(b)

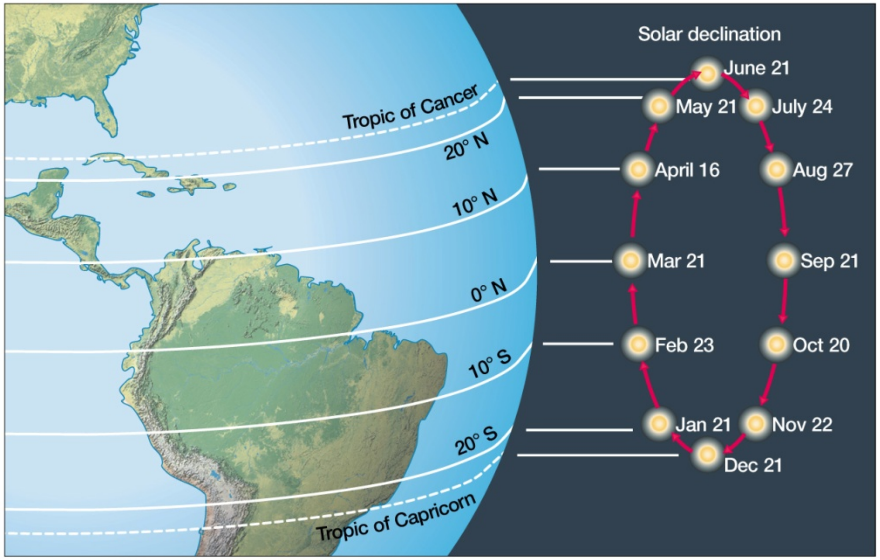
The Annual March of the Seasons

- **Significance of seasonal patterns**
  - Spread of solar rays over small and large areas
  - Tropical latitudes consistently warmer
  - Polar latitudes consistently cooler
  - Large seasonal variations in temperature in midlatitudes

The Seasons

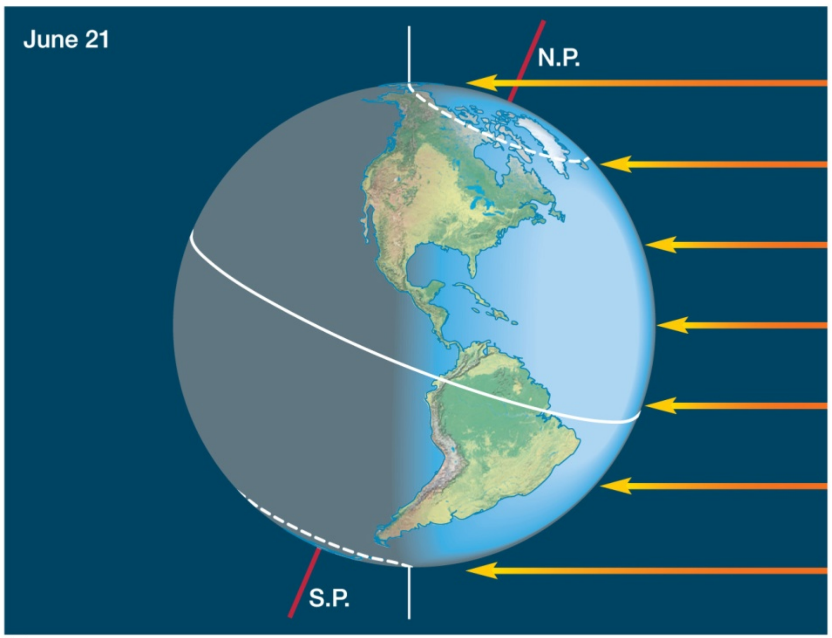
- Summer and Winter Solstices



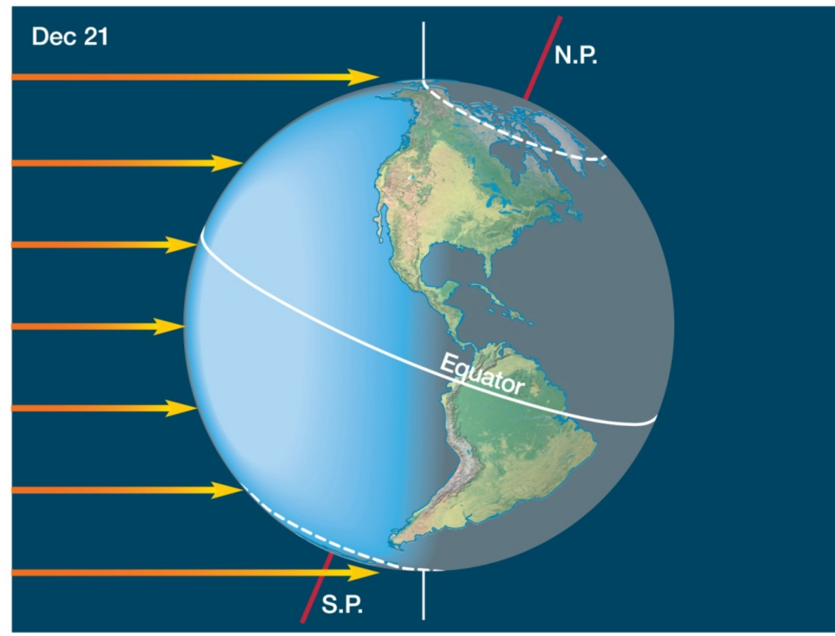


Seasons

- Summer and Winter Solstices



(a)



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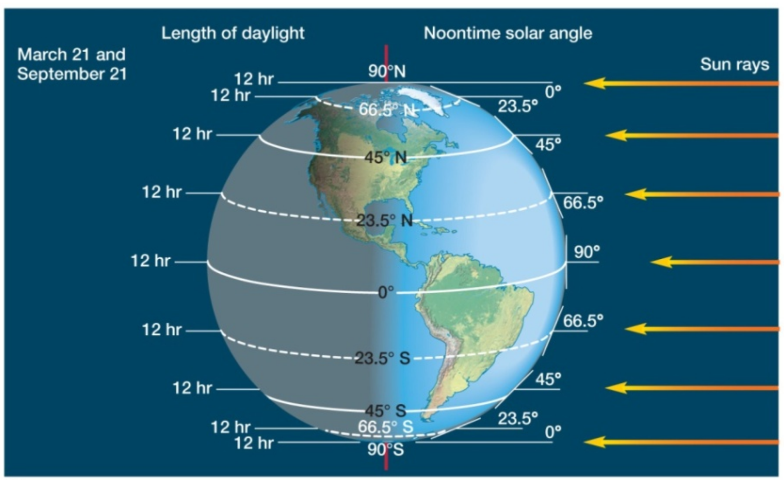
Seasons

- Equinox: March 21 and September 21



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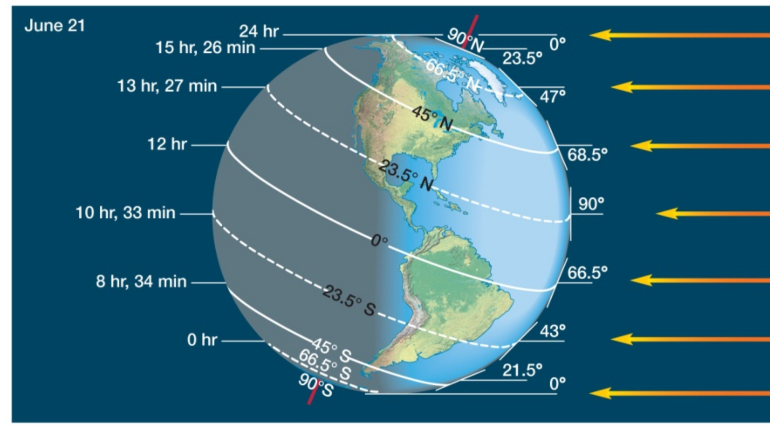

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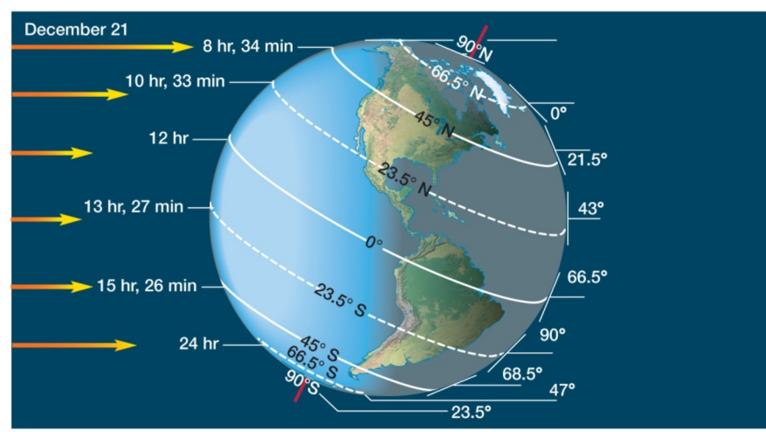

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The Annual March of the Seasons

- **Day length**
  - Always 12 hours at the equator
  - In the Northern Hemisphere, day length increases after March equinox
  - Maximum day length during June solstice in Northern Hemisphere
  - Opposite for Southern Hemisphere

TABLE 1-7 Day Length at Time of June Solstice

Latitude	Day Length	Noon Sun Angle (degrees above horizon)
90° N	24 h	23.5
80° N	24 h	33.5
70° N	24 h	43.5
60° N	18 h 53 min	53.5
50° N	16 h 23 min	63.5
40° N	15 h 01 min	73.5
30° N	14 h 05 min	83.5
20° N	13 h 21 min	86.5
10° N	12 h 43 min	76.5
0°	12 h 07 min	66.5
10° S	11 h 32 min	56.5
20° S	10 h 55 min	46.5
30° S	10 h 12 min	36.5
40° S	09 h 20 min	26.5
50° S	08 h 04 min	16.5
60° S	05 h 52 min	6.5
70° S	0	0
80° S	0	0
90° S	0	0

Source: After Robert J. List, *Smithsonian Meteorological Tables*, 6th rev. ed. Washington, D.C.: Smithsonian Institution, 1963, Table 171.

Changes in Energy Receipt with Latitude

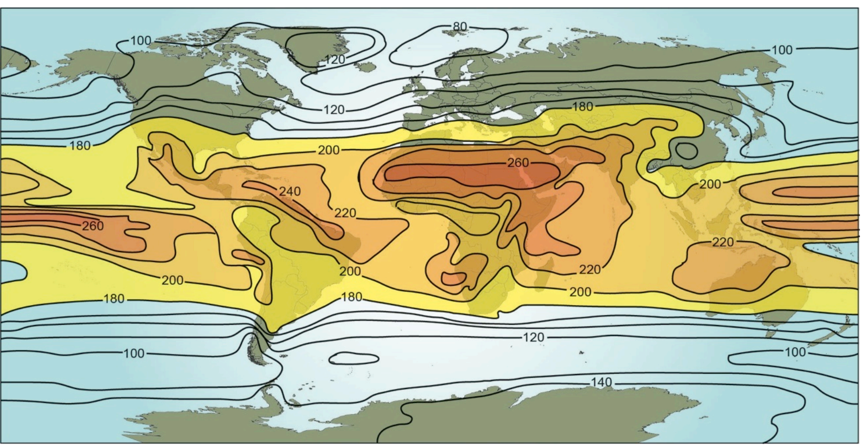
TABLE 2–2

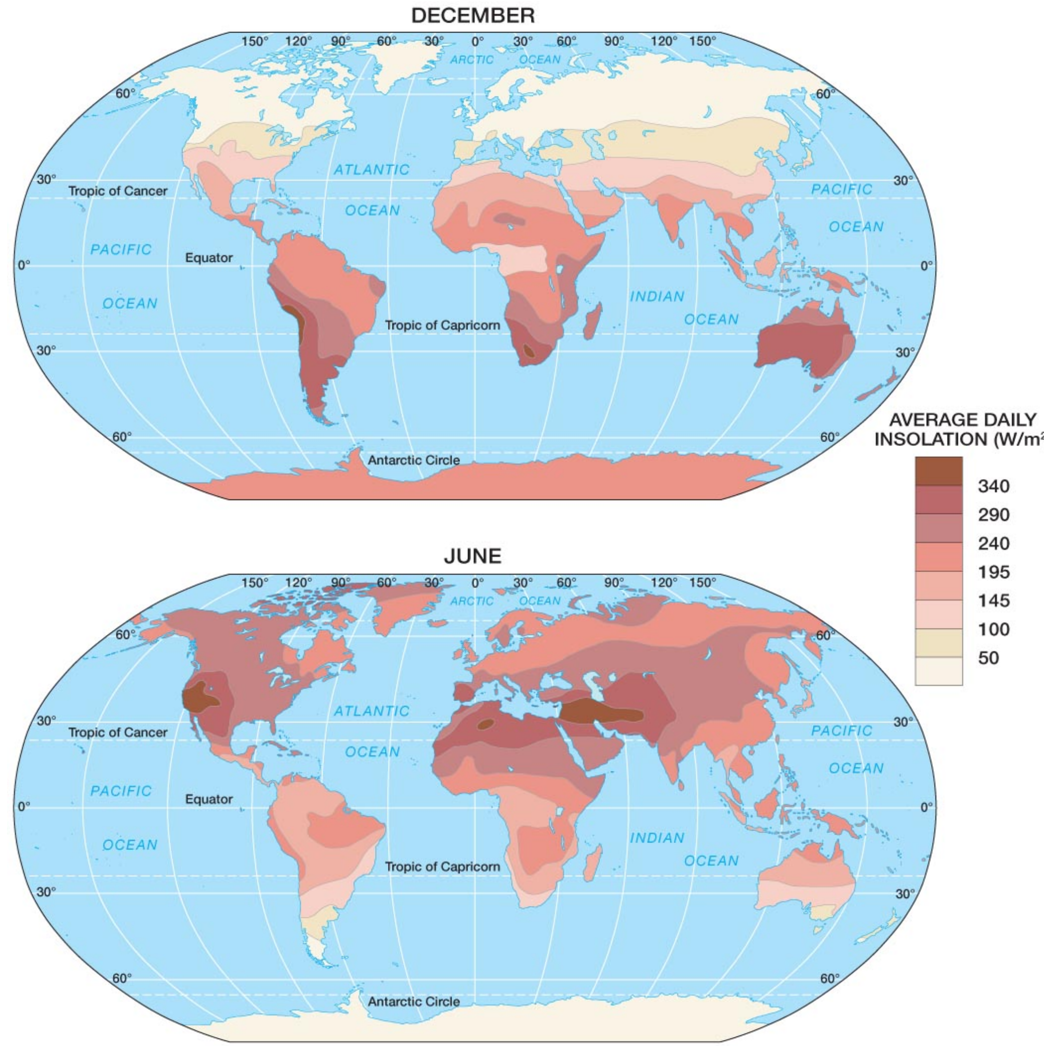
Variations in Solar Angle and Daylength

	Solar Angle at Noon	Length of Day	Total Radiation for Day (Megajoules m^2)
December 21			
Winnipeg (50° N)	16.5°	7 hr, 50 min	7.1
Austin (30° N)	36.5°	10 hr, 04 min	18.6
June 21			
Winnipeg (50° N)	63.5°	16 hr, 10 min	44.5
Austin (30° N)	83.5°	13 hr, 56 min	43.9

Variations in Heating by Latitude and Season

- World distribution of insolation
- Clouds strongly influence the distribution of insolation
- Where do we have clouds?





Telling Time

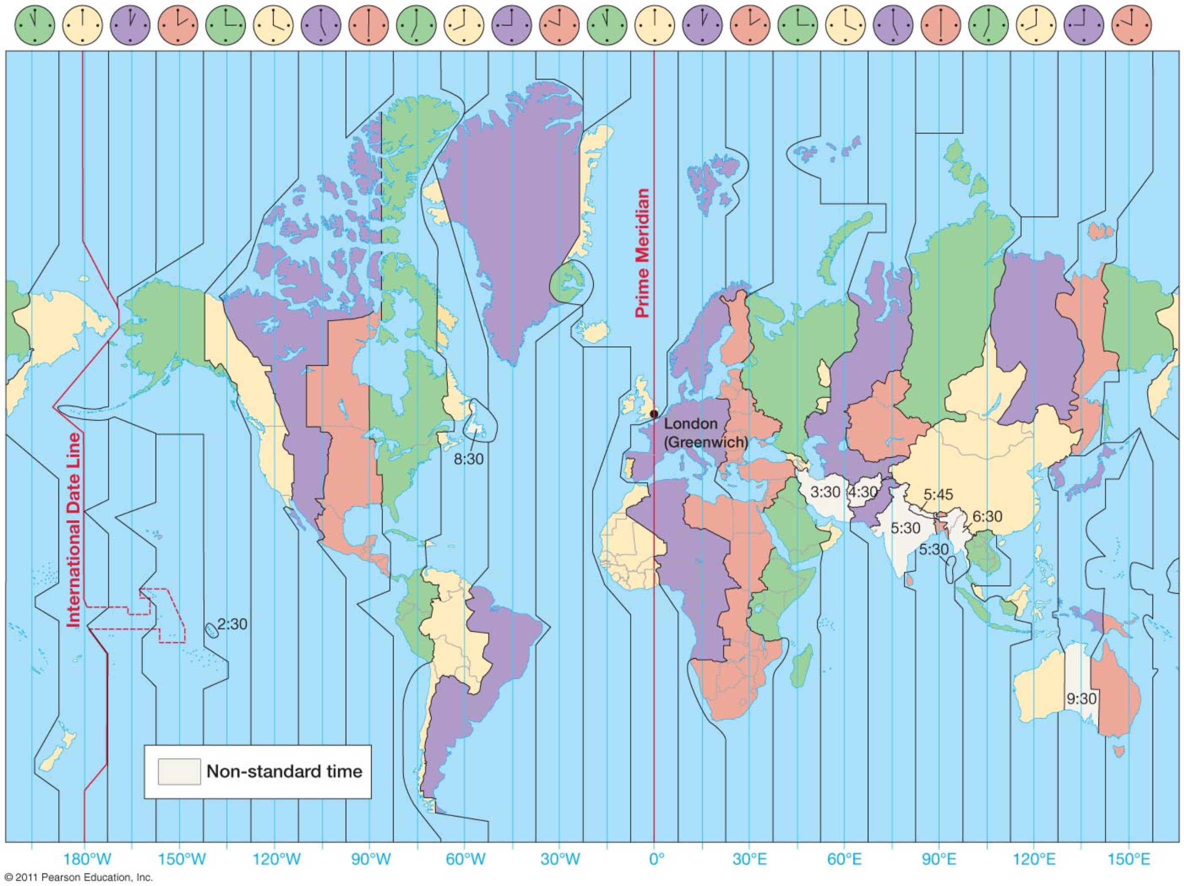
- Current time system
  - 24 time zones
  - Greenwich Mean Time (GMT) is standard. It is now more commonly known as Universal Time Coordinated (UTC)
  - Several countries have multiple time zones in their borders
  - Time zone boundaries subject to local political and economic boundaries of different nations
  - 180° meridian chosen as the International Date Line

Telling Time

- Time zones of the United States

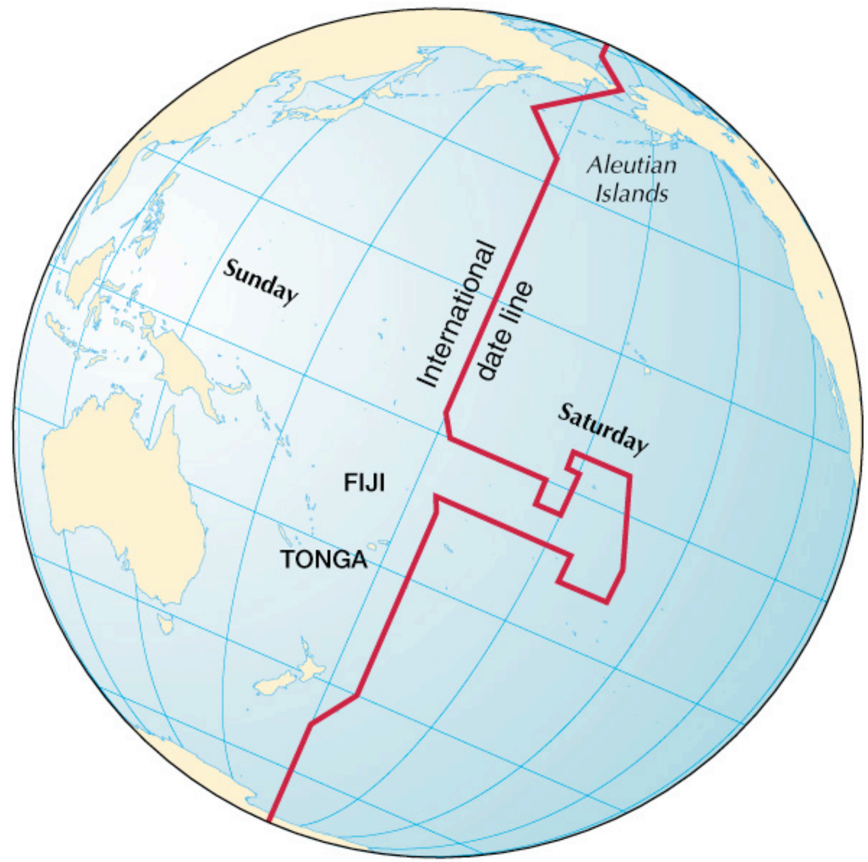
Telling Time

- Time zones of the world



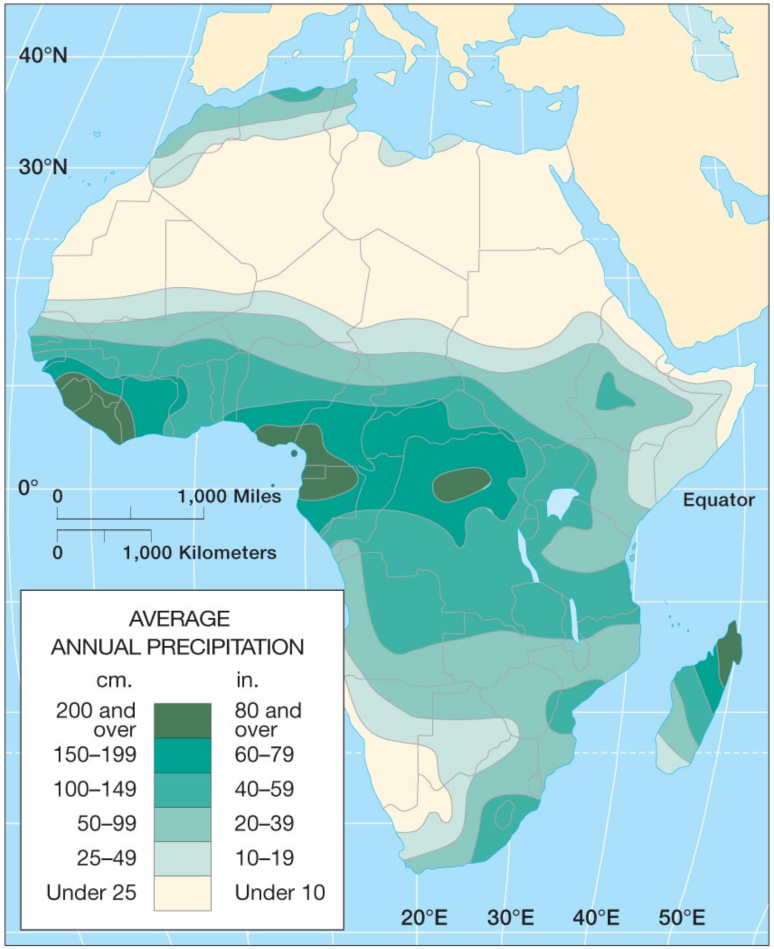
Telling Time

- International date line
  - Situated in the Pacific
  - When crossing from west to east it becomes one day earlier
  - When crossing from east to west it becomes one day later



Isolines

- Many maps display information with isolines
- Isolines join point of equal value
- Many of these isolines have been given special names:
  - Elevation contour line
  - Isobar: line of constant pressure
  - Isotherm: line of constant temperature
  - Isohyet: line of constant rain



Temperature conversions

	Water boils	Water freezes	Absolute zero
Fahrenheit (F)	212	32	-459.67
Celsius (C)	100	0	-273.15
Kelvin (K)	373.15	273.15	0

- °C = K – 273
- K = °C + 273
- °C = (°F – 32)*5/9
- °F = (°C)*9/5+32
- 233K = -40 °C = -40 °F
- 184K = -89.2 °C = -128.6 °F = coldest official thermometer reading; Vostok, Antarctica, July 21, 1983
- 330K = 56.7 °C = 134 °F = highest official thermometer reading (two meters above the ground and in the shade); Death Valley, CA, July 10, 1913

Climate versus weather

- climate is the average of weather statistics over a long time (varies slowly – long term patterns)
- climate is a boundary value problem focused on long term equilibrium behavior (not transient behavior)
- weather is the state of the atmosphere in a particular region at a given time (varies quickly – short term phenomena)
- weather is an initial value problem that requires solving the highly non-linear, chaotic Navier-Stokes equations of fluid motion – small differences in initial conditions diverge quickly

Chemical composition of the atmosphere

- Permanent gases
  - N_2, O_2
- Variable gases
  - H_2O, CO_2, O_3

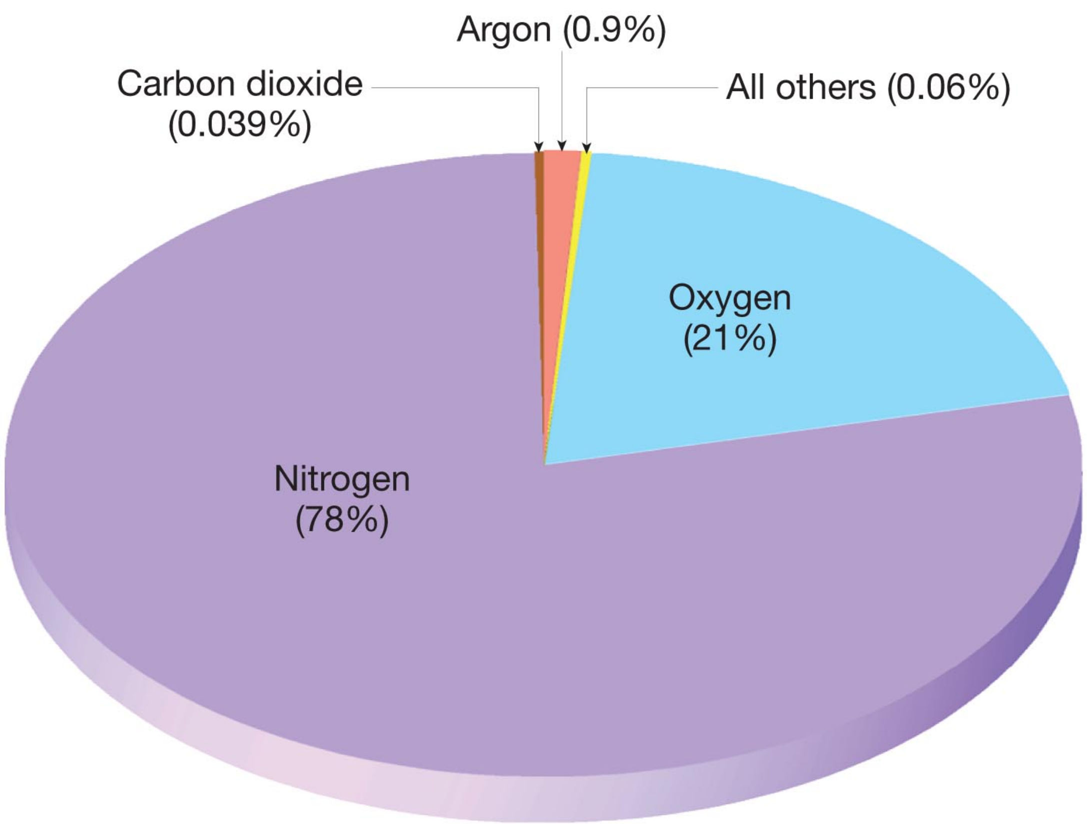


TABLE 3-1 Principal Gases of Earth's Atmosphere

	Percent of Volume of Dry Air	Concentration in Parts per Million Parts of Air
Permanent gases		
Nitrogen (N_2)	78.084	
Oxygen (O_2)	20.946	
Argon (Ar)	0.934	
Neon (Ne)	0.00182	18.2
Helium (He)	0.00052	5.2
Krypton (Kr)	0.00011	1.1
Hydrogen (H_2)	0.00005	0.5
Variable gases		
Water vapor (H_2O)	0–4	
Carbon dioxide (CO_2)	0.039	390
Carbon Monoxide (CO)		<100
Methane (CH_4)	0.000178	1.78
Ozone (O_3)		<2
Sulfur dioxide (SO_2)		<1
Nitrogen dioxide (NO_2)		<0.2

Aerosols

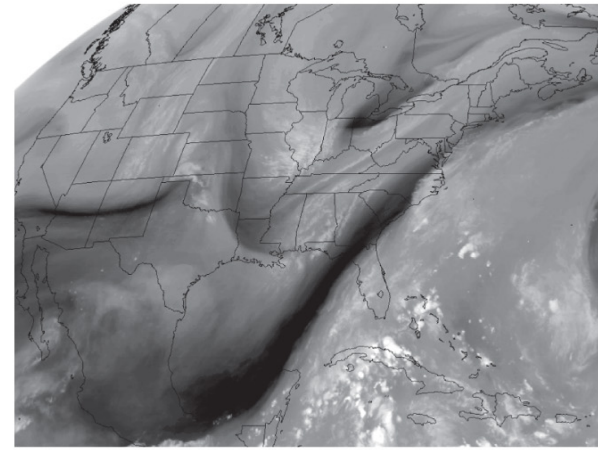
- **Aerosols** are any solid and/or liquid particle, other than water, which exists in the atmosphere (synonymous with the term particulate).
- Aerosols are both natural (sea spray, dust, volcanoes) and human (combustion) produced products.
- Due to their small size, they can easily remain in suspension for long periods.
- Aerosols contribute to precipitation processes as **condensation nuclei**.
- Some aerosols reflect more energy than they absorb and have a cooling effect (sulfates are a prime example)
- Some aerosols absorb more energy than they reflect and have a warming effect (black carbon is a prime example)

Functional Role of Different gases

- Variable Gases: Water Vapor
  - **<u>Water vapor</u>** is the most abundant variable gas, as it is added or removed from atmosphere through the hydrologic cycle.
  - Concentrations exist from nearly 0% over desert and polar regions to nearly 4% near tropics.
  - Water vapor is a contributor to Earth's energy balance and many important atmospheric processes
  - The vast majority of the atmospheric water vapor is in the troposphere (lowest level of the atmosphere)

Composition of the Atmosphere

- Variable Gases: Water Vapor
  - Water vapor image showing broader distribution of moisture than the image of actual clouds (below).



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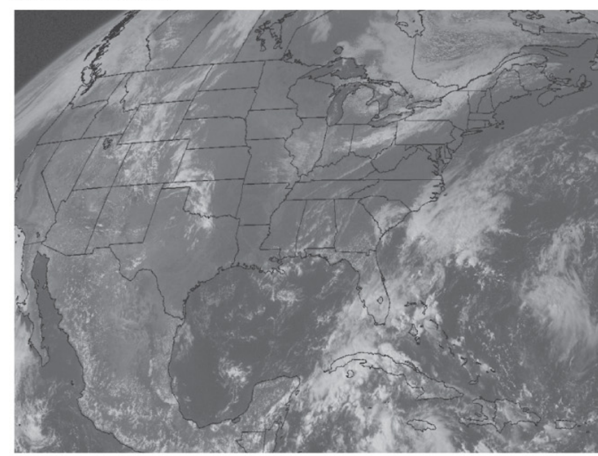

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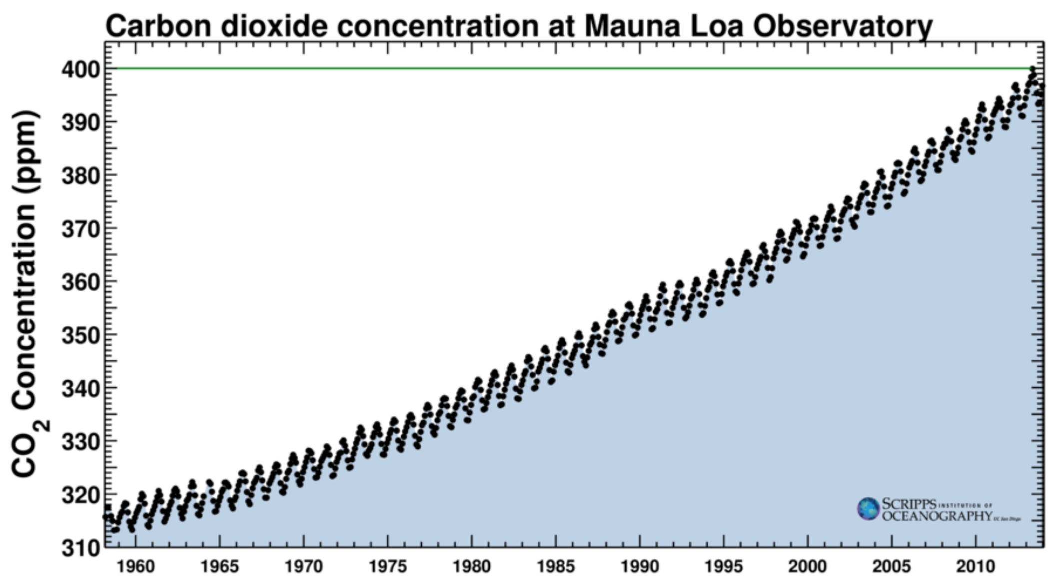
Composition of the Atmosphere

- Variable Gases: Carbon Dioxide
  - **Carbon dioxide** is a trace gas accounting for 0.0395% of the atmosphere's volume.
  - CO_2 is important to Earth's energy balance.
  - The Swedish Nobel laureate chemist Svante Arrenhius showed that CO_2 had warming potential in the 1890s
  - CO_2 is added through biologic respiration, volcanic activity, decay, and the combustion of fossil fuels
  - CO_2 is removed through **photosynthesis**, the process by which plants convert light energy to chemical energy
  - Although less potent on a per-molecule basis than other greenhouse gases, CO_2 bears responsibility for the largest share of human induced climate change

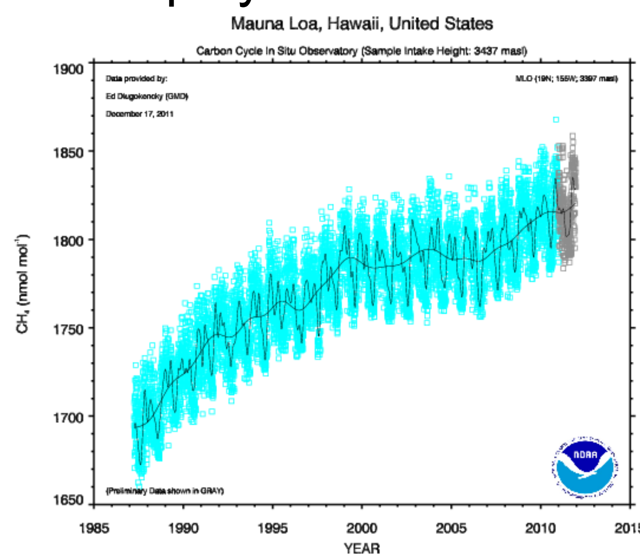
The Keeling curve and CO_2 over time

- Since 1958, there have been direct atmospheric measurements of CO_2, methane and other greenhouse gases at the Mauna Loa Observatory in Hawaii. This was started by Charles David Keeling. The time series of CO_2 is monotonic – increasing from 315 ppmv in 1958 to 400 ppmv in 2013



Composition of the Atmosphere

- Variable Gases: Methane CH_4
  - **<u>Methane</u>** is a variable gas in small but recently increasing concentrations.
  - Released to the atmosphere through natural sources (decay and wetlands), fossil fuel activities, livestock digestion, and agriculture cultivation (esp. rice).
  - Methane works as a very effective absorber of terrestrial radiation (on a molecule by molecule basis) and it plays an active role in near surface warming.

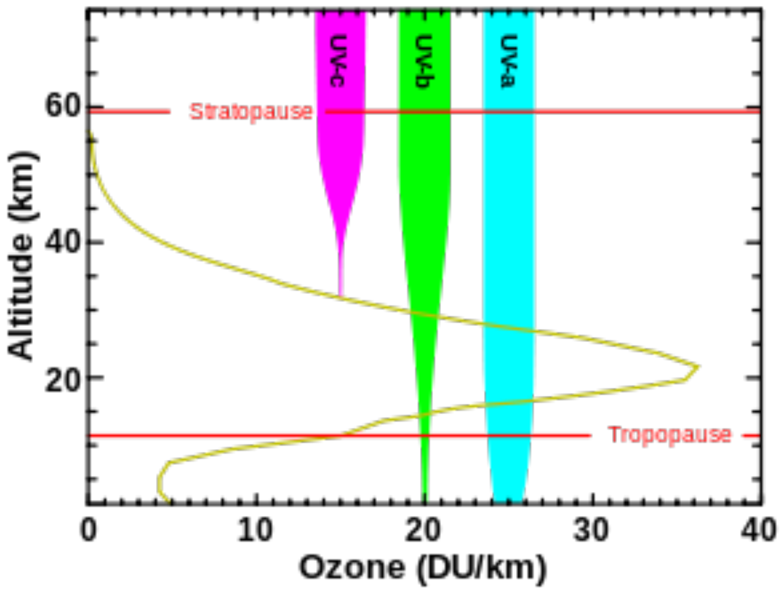


Annual increases in atmospheric methane.

Composition of the Atmosphere

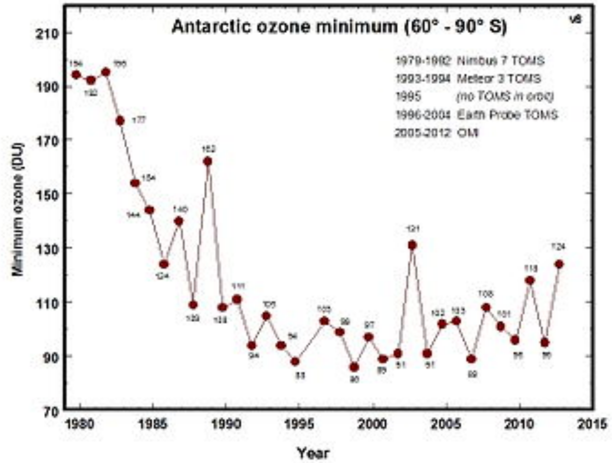
- Variable Gases: Ozone O_3

- **Ozone** is the tri-atomic form of oxygen and is essential to life on Earth.
- Ozone near the surface is a pollutant and greenhouse gas but in the stratosphere it is an essential absorber of ultraviolet radiation.
- Chlorofluorocarbons (CFCs), specifically chlorine atoms, react with ozone in the stratosphere and destroys ozone causing an “ozone hole”
- Ozone destruction peaks over the southern hemisphere and persists through spring.

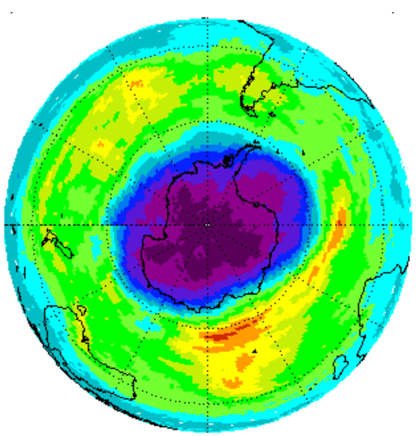


Composition of the Atmosphere

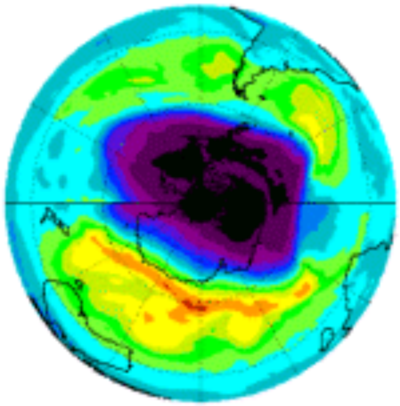
- Variable Gases: Ozone
  - Because of the effect of CFCs on the stratospheric ozone concentration, the Montreal Protocol of 1987 was signed to limit further production of CFCs
  - As a consequence, the ozone hole that formed in the late 1980s has begun to show some modest signs of stabilization



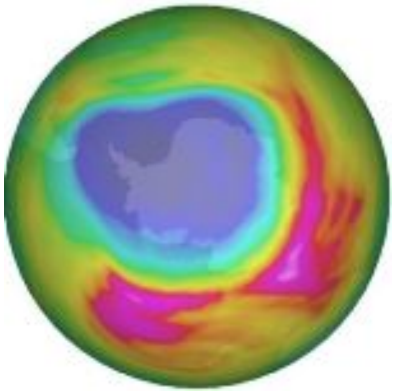
1987



2006

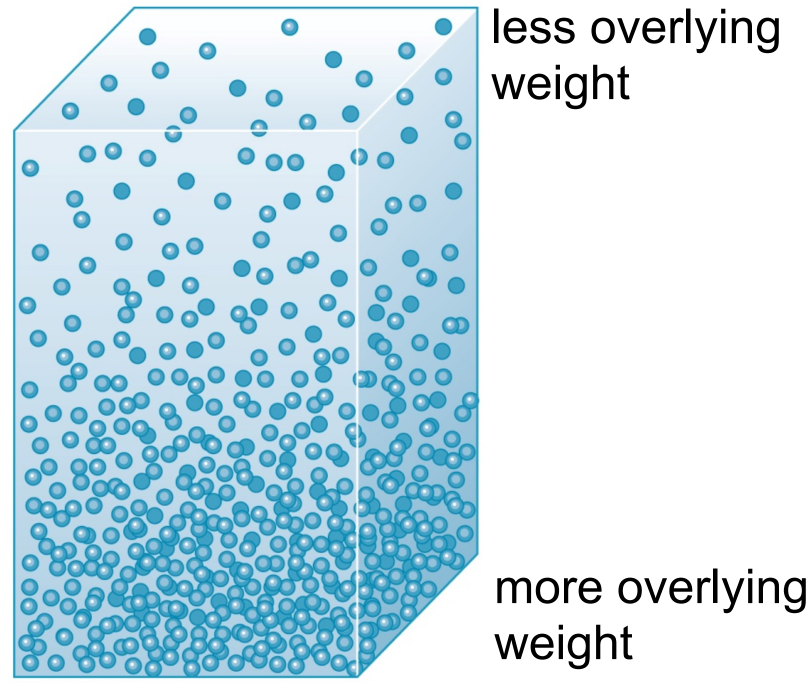


2012



Density

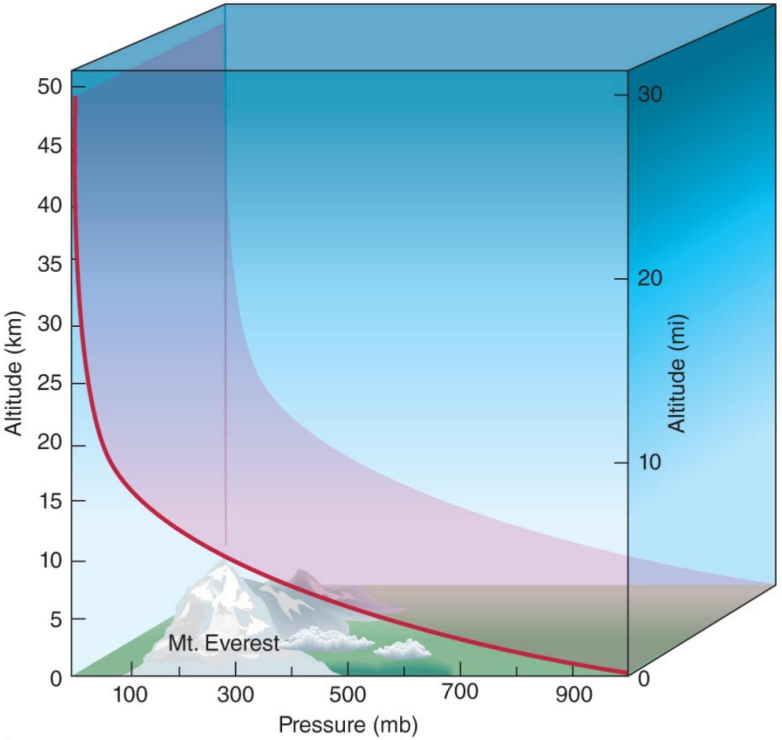
- **<u>Density</u>** is mass (kg) per unit volume (m^3).
- Due to compressibility, near surface air is more dense than that above.
- This may be expressed in terms of the mean free path, or average distance a molecule travels before colliding with another molecule.
- Density decreases exponentially with elevation



Due to compressibility, atmospheric mass gradually “thins out” with height.

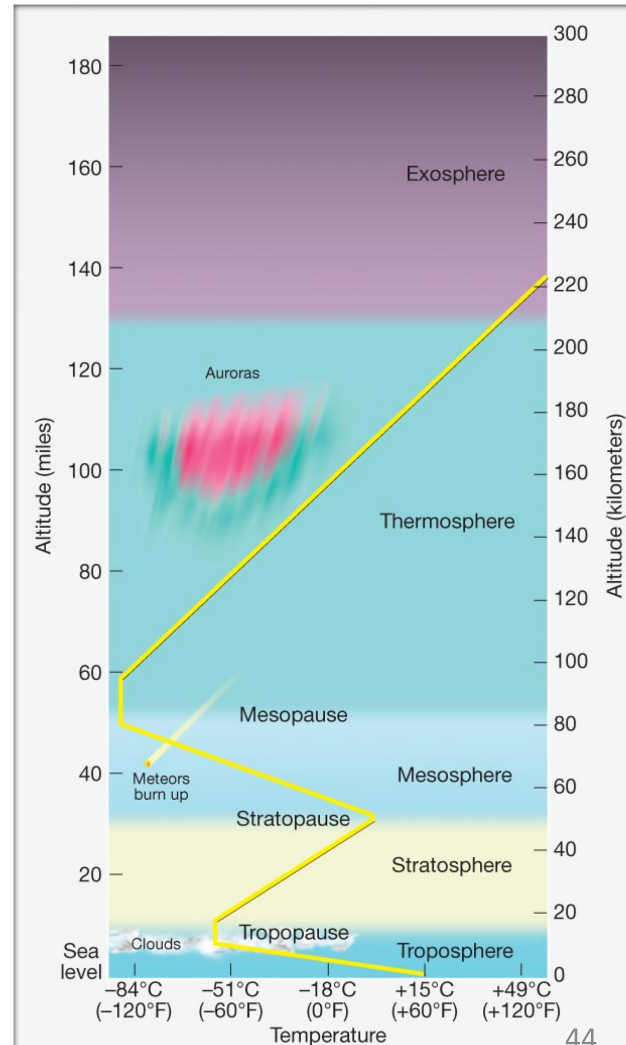
Pressure

- **<u>Pressure</u>** is a result of the atmosphere's mass.
- Pressure decreases vertically, but at an exponential, rather than linear rate
- the atmospheric pressure and density are about 40% of sea level pressure and density at the summit of Mt. Everest



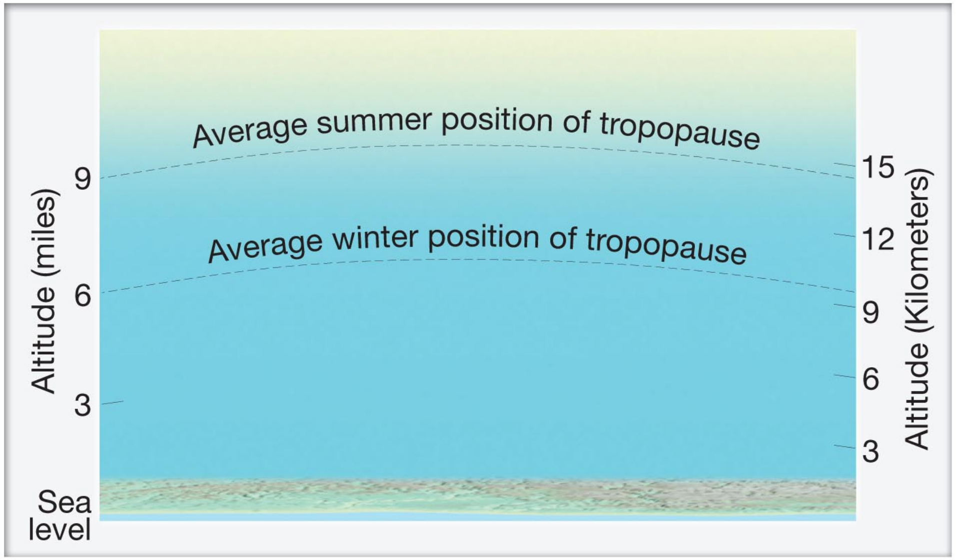
Vertical thermal structure of the atmosphere

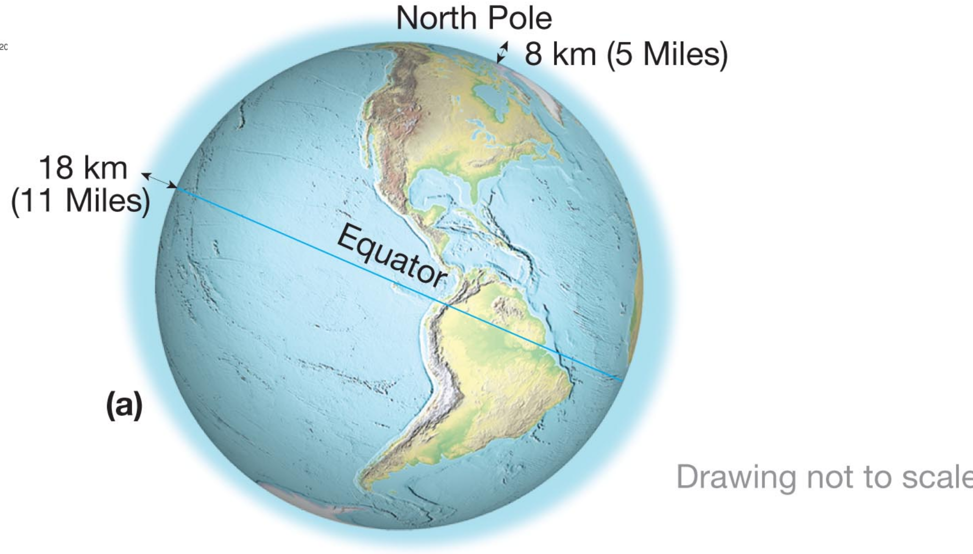
- Troposphere – temperature decreases with altitude
- Stratosphere – temperature increases with altitude (due to UV absorption by ozone)
- Mesosphere – temperature decreases with altitude
- Thermosphere – temperature increases with altitude (due to UV absorption by ionized gases)
- Exosphere – temperature decreases with altitude



Troposphere

- The **<u>troposphere</u>** is the lowest layer, named as this region promotes atmospheric overturning.
- Layer of virtually all weather processes.
- Warmed at the surface by solar radiation.
- Identified by a steady temperature decrease with height and as the thinnest layer (but contains 80% of the mass).
- Due to thermal expansion, the **tropopause** is roughly 16 km over the tropics, but only 8 km at poles.



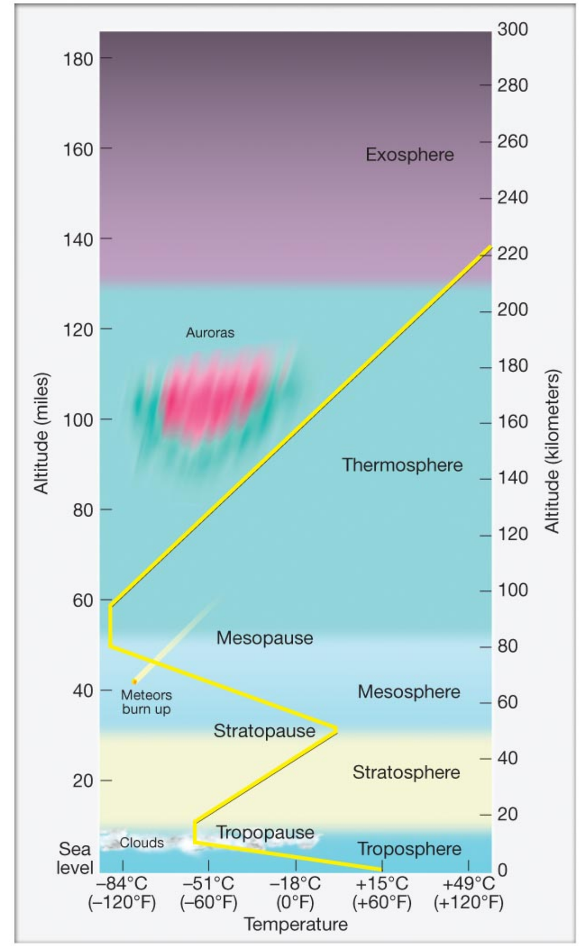


Vertical Structure of the Atmosphere

- Most clouds exist in the troposphere. Occasionally, violent updrafts penetrate cloud tops into the stratosphere. The flattened tops of these cumulonimbus clouds are in the stratosphere.
- Tropopause – boundary between troposphere and stratosphere

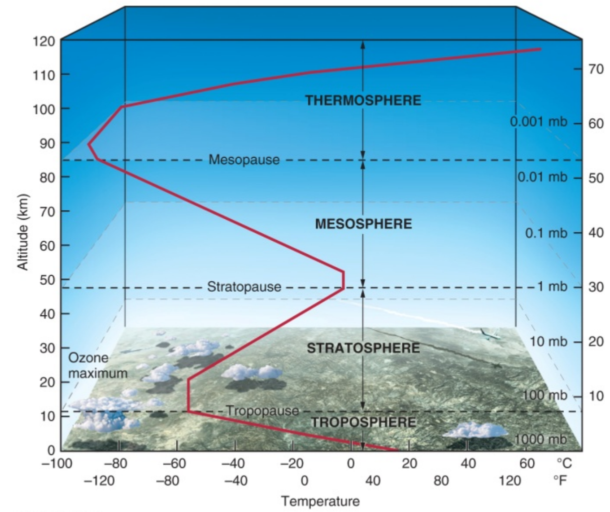
Stratosphere

- The **stratosphere** is an area of little weather ("stratified") and the temperature increases with height
- Temperature inversion caused by the absorption of ultraviolet radiation by ozone
- Stratosphere extends from tropopause to stratopause about 50 km above the surface
- Stratosphere contains almost all the mass of the atmosphere not in the troposphere
- Although the ozone layer exists through an altitude between 20–30km (12–18mi), actual concentration of ozone can be as low as 10ppm.



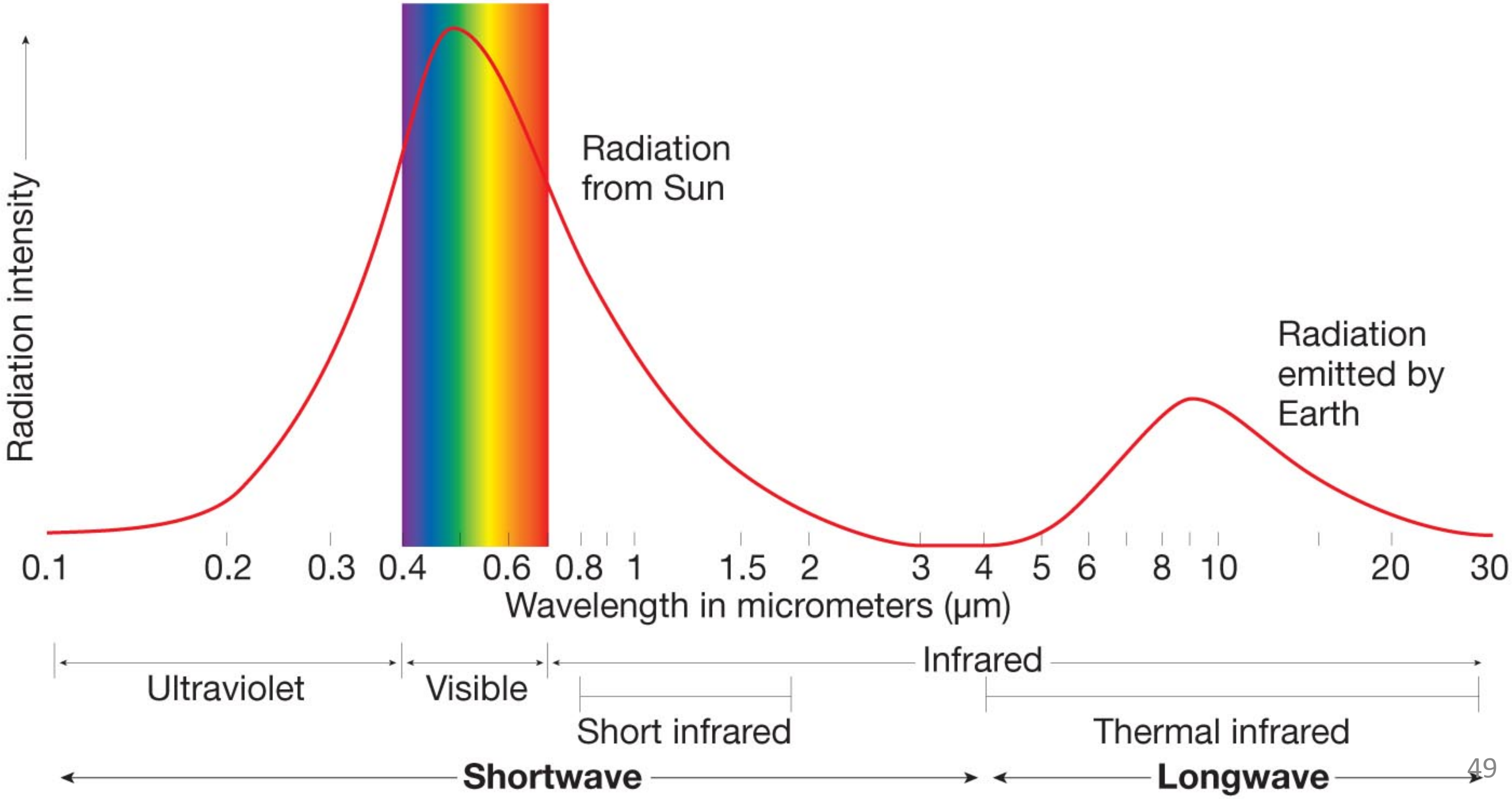
Mesosphere and Thermosphere

- **<u>Mesosphere</u>** is characterized by decreasing temperatures with height and is the coldest atmospheric layer – extends to about 85 km elevation
- **<u>Thermosphere</u>**, the upper most layer; slowly merges with interplanetary space and is characterized by increasing temperatures with height.
- Temperatures approach 1500°C, however, this only measures molecular kinetic energy as the sparse amount of mass produces little actual heat content.
- Auroras occur in the thermosphere
- Combined the two layers account for only 0.1% of total atmospheric mass.



Radiation

- Wien's law: $\lambda_{max} = 0.29/T_{em}$, where λ_{max} is the wavelength (in cm) of maximum emission and T_{em} is the emission temperature in K



Principles of Blackbody Radiation

- A blackbody radiator emits energy in proportion to the 4th power of the absolute temperature in K, according to the
- Stefan-Boltzmann law: energy emitted = kT^4, where k is the Stefan-Boltzmann constant, $5.67*10^{-8} W/m^2/K^4$
- At equilibrium, a blackbody will emit the same amount of radiation it absorbs

Albedo/reflectivity

- Albedo is a term that quantifies the reflectivity of a surface.
- A surface with high albedo reflect a lot of radiation relative to how much it received.

Radiative equilibrium for no atmosphere

- The intensity of the Sun's energy, S, is about 1367 W/m^2 at the 93 million mile orbital distance of the Earth
- The Earth effectively intercepts a circle of radiation from the sun, but the Sun's radiation is distributed over the sphere of the Earth, so the solar constant is divided by 4 (the area of a circle is πr^2 and the surface area of a sphere is $4\pi r^2$)
- Further, a portion of the solar energy is reflected – this is known as the planetary albedo or reflectivity "a". The planetary albedo of Earth is about 0.3 or 30%
- Consequently, if there is no atmosphere, the balance becomes

$$\frac{S(1-a)}{4} = kT^4$$

- The surface temperature, under this assumption of no atmosphere is therefore about 255 K, which is -18C or about 0 F

Radiative equilibrium for a single - plane atmosphere

- In a one plane atmosphere that is assumed to be transparent to incoming solar radiation and partially opaque to outgoing longwave radiation (OLR) from the Earth, we have

$$f_{abs} k T_S^4 = k T_A^4$$

At the atmosphere, where f_{abs} is the fraction of the outgoing longwave radiation the atmosphere absorbs, T_A is the temperature of the atmosphere and T_S is the temperature of the surface and

$$\frac{S(1-a)}{4} + 0.5 k T_A^4 = k T_S^4$$

At the surface

It is evident that as f_{abs} increases (through increasing absorption of OLR), T_A and T_S also increase. To properly simulate Earth's observed global mean surface temperature of 287K (14C or 57 F), f_{abs} would be about 0.93 in this simplified equation.

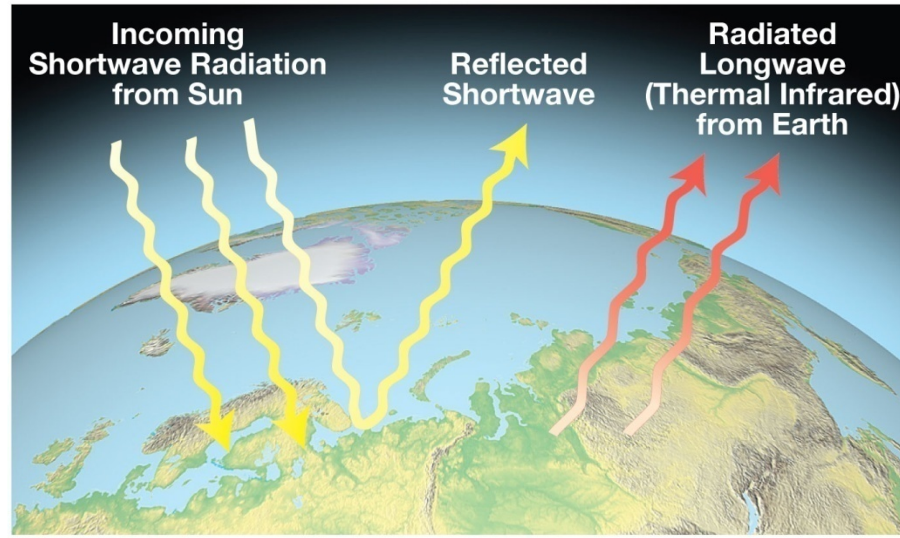
The added anthropogenic greenhouse effect is tantamount to increasing f_{abs}.

Real radiative balance

- For more complex models of Earth's atmosphere (and especially for planets with thick atmospheres and runaway greenhouse effects like Venus), a multi-layered atmosphere must be considered. For multi-layered atmospheres, much higher surface temperatures are theoretically (and actually) possible.
- In reality, as the surface warms, the tropopause actually cools. The mean radiating height of the planet is around 5.5km (about midway through the atmosphere's mass), but the tropopause is a fair amount higher). The more energy absorbed by the troposphere in a warmer world, the cooler the tropopause and colder the stratosphere will become.

The Heating of the Atmosphere

- In the long run, there is roughly a balance between shortwave incoming solar radiation and outgoing longwave solar radiation
- If there is no balance, the earth’s temperature will be affected (e.g. global warming)



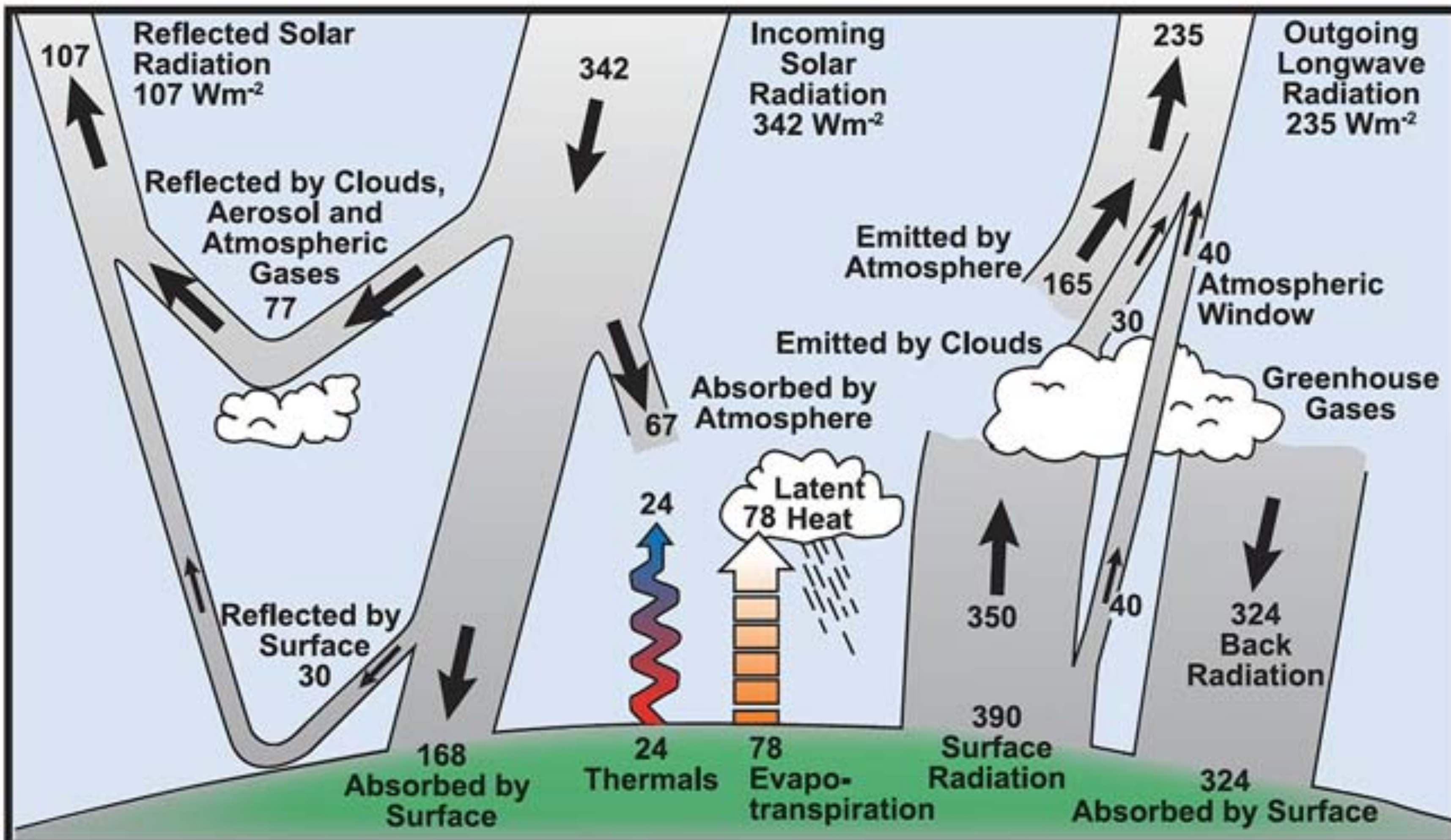
The Heating of the Atmosphere

- Animation that traces the fate of 100 units of solar energy as it reaches the top of the atmosphere.

- http://earthguide.ucsd.edu/earthguide/diagrams/energybalance/index.html

The Heating of the Atmosphere

- Global energy budget



Anthropogenic greenhouse effect overview

- The increase in greenhouse gas concentrations in the troposphere increases the absorption of the outgoing long-wave radiation from the Earth's surface and some of that energy is re-radiated back to the surface, causing an elevation of surface temperature
- Greenhouse gases:

water vapor H_2O – natural sources and temperature feedback

carbon dioxide CO_2 – natural sources and fossil fuel combustion, deforestation

methane CH_4 – natural sources and livestock and rice paddy cultivation, landfill outgassing, fossil fuel combustion

tropospheric ozone O_3 – natural sources and indirect production from automotive exhaust

nitrous oxide N_2O – natural sources and used as a medical anesthetic

chlorofluorocarbons, hydrofluorocarbons – used as refrigerants and for other applications (no natural source)

- Aerosols have a mixed effect
- Clouds have a mixed effect

The role of skepticism in science and political discourse

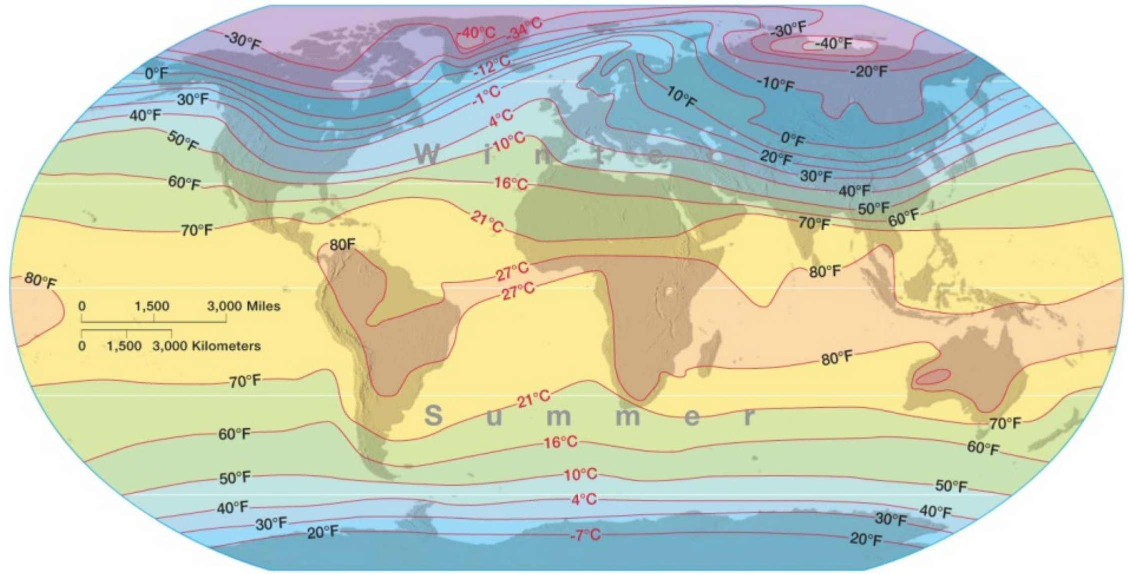
- Skepticism plays a vital role in scientific discourse and in intelligent political discourse: indeed many scientific discoveries and many wise policy choices would not have been possible without a willingness on the part of the catalyst to challenge convention
- In either arena, however, there ***should*** be a sense of responsibility on the part of the "skeptic" to go beyond merely disagreeing and to offer evidence criticizing the convention and if possible, evidence to support an alternative idea
- However, in science, this is the minimum standard and expectation - scientific skepticism does not consist of simply disagreeing with a prevailing theory – one must have ***evidence:*** either by countering the theory by finding flaws in its deduction or induction or by countering the reported observations with new experimental and/or observational evidence
- Climate "skeptics" have failed to produce observational evidence that can explain the rise in greenhouse gases without human involvement and have failed to produce a cogent refutation of the underlying theory based on radiative balance physics and the known radiative properties of greenhouse gases.
- Belief is ***not*** evidence!

Why the climate change “skeptics” are wrong

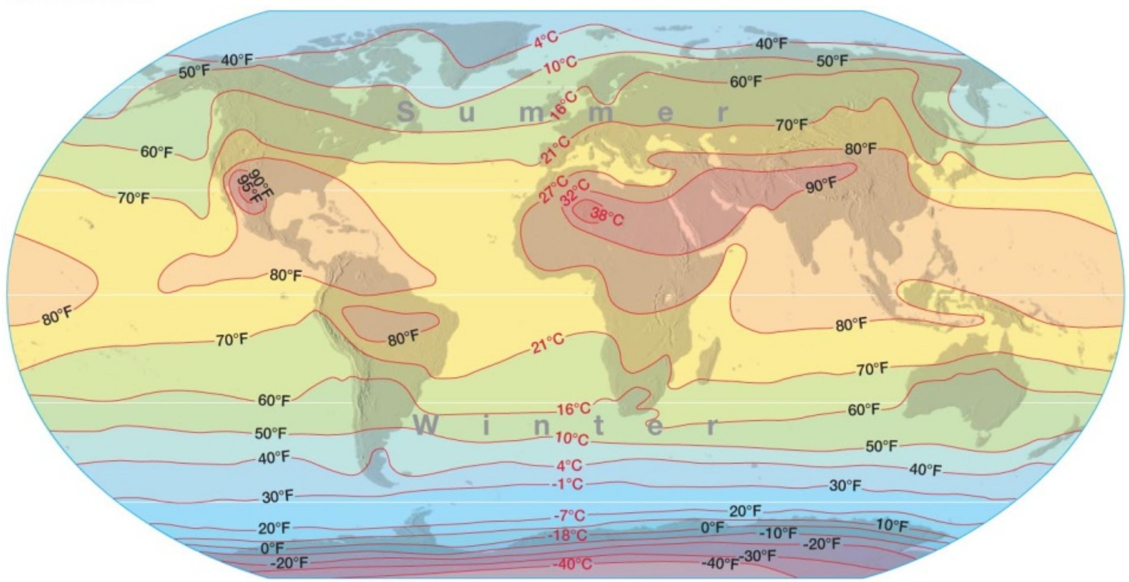
- The fact that it has been cold and snowy in much of the eastern and central US this January does ***not*** disprove the premise of global climate change caused by mankind.
- The skeptics tend to focus on changes in temperature or the fact that in the paleoclimate record, there have been warmer times
- What they are missing is how unusual the greenhouse gas concentrations are and they fail to produce any meaningful explanation of the GHG concentrations without human involvement
- Focusing on the extremes in Earth’s history as a justification for inaction is also foolish – there is abundant evidence that massive climate changes in the Earth’s past have been accompanied by massive changes in the sea level and high rates of extinction

Global Mean Temperatures with Season

average
January
temperature

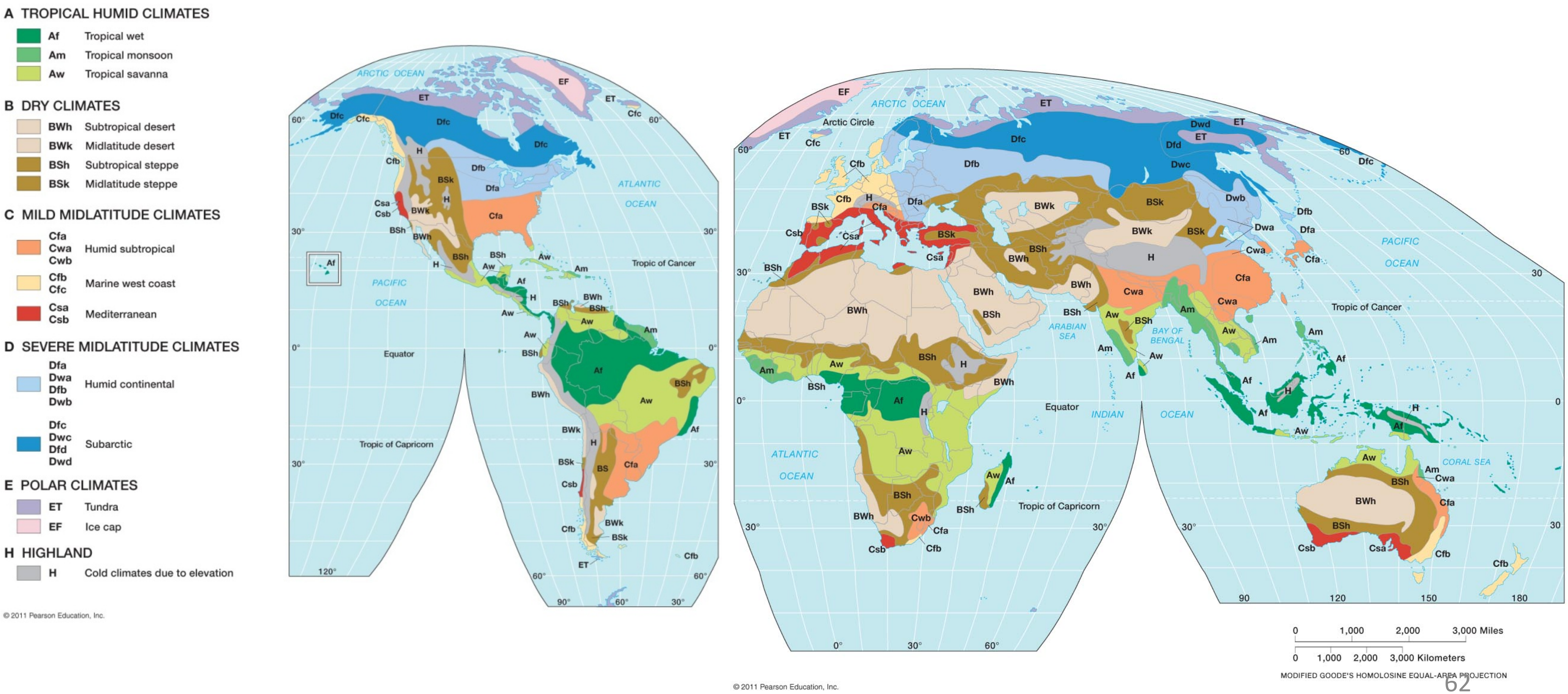


average
July
temperature



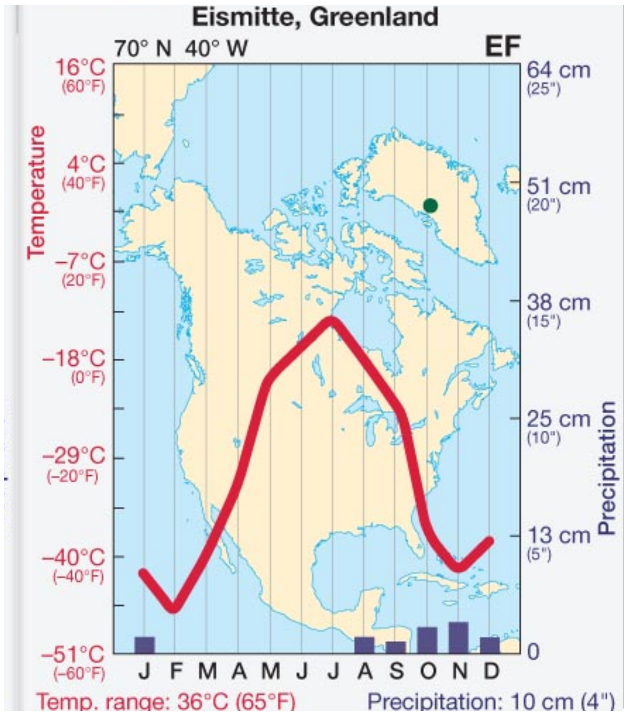
Koppen Climate Classification System

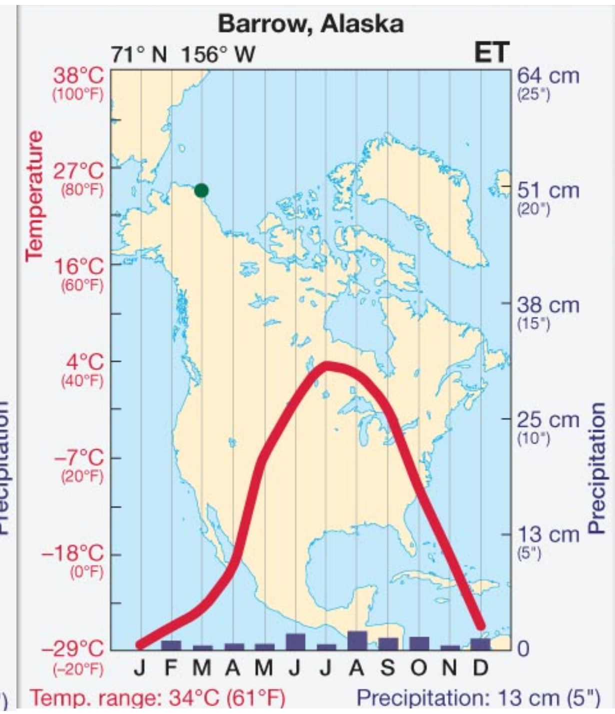
- Classification of climate type primarily on temperature and precipitation
- Climograph – graph representing regional climatological rainfall and temperature in the different months of the year

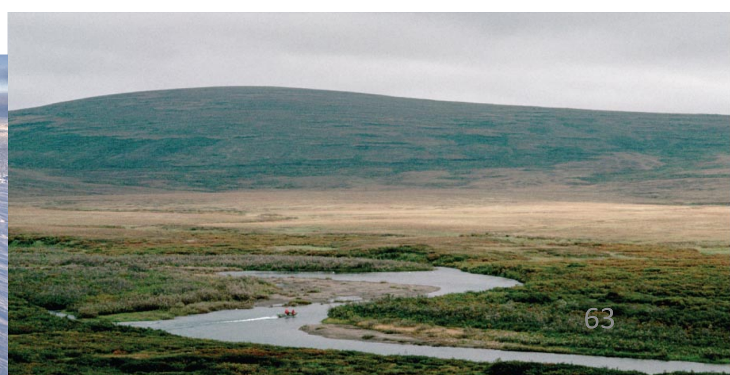


Climates of the world: polar/high latitude climates

- Ice cap – extremely cold winters (average winter temperatures -25 C and below), ice covered all year, cold summers (often below 5C), for the most part fairly arid (less than 40cm/year)
- Tundra – extremely cold winters, cool to moderate summers (0-15C), stunted, shrub-like vegetation, continuous permafrost, arid (less than 40cm/year)

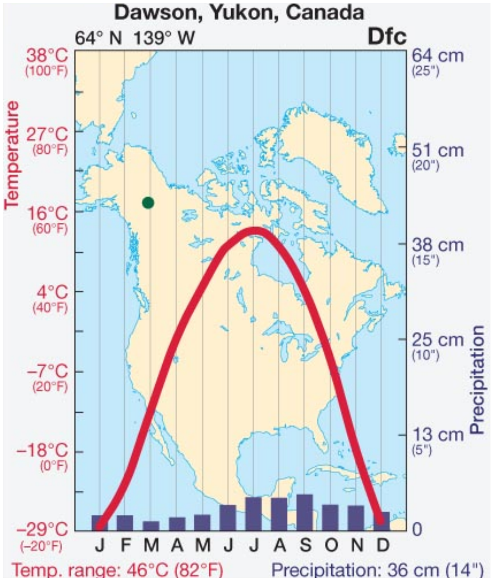






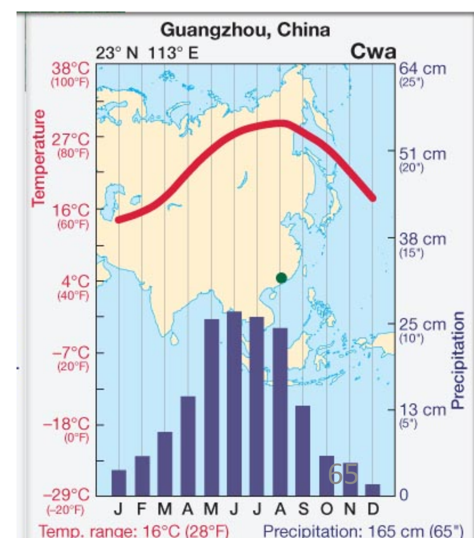
Climates of the world: subarctic/ boreal climates

- Taiga/boreal forest – extremely cold winters, moderate to warm summers (15 to 25C), forests are exclusively conifers, precipitation varies



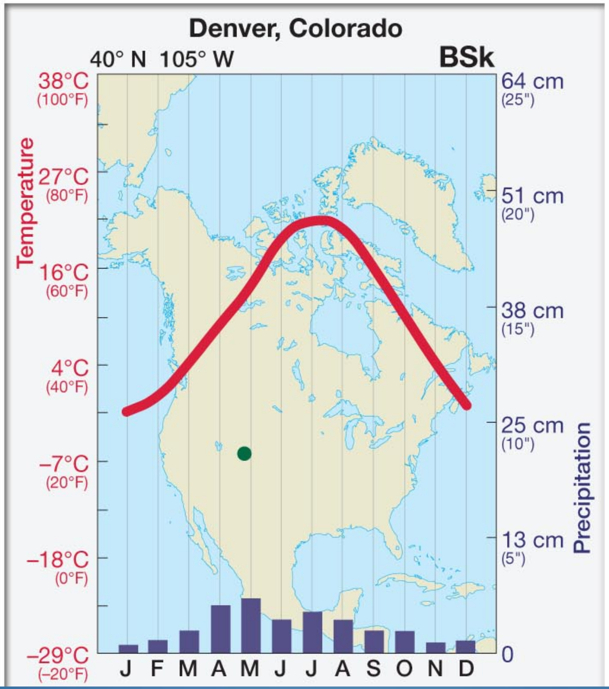
Climates of the world: continental mixed and deciduous forest

- Mixed forest: very cold winters (averages -5 to -25C), warm summers (25 to 30C), mix of coniferous and deciduous trees, rainfall varies, but usually a little wetter than taiga
- Deciduous forest: warm to hot summers (25 to 35C), cold winters (-10 to +10C), trees lose their leaves in the fall, rainfall fairly abundant (90-160cm)



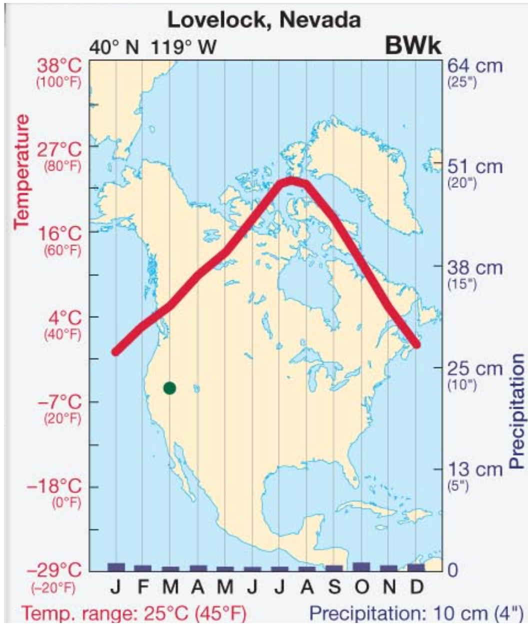
Climates of the world: continental grassland

- Warm to Hot summers (25 to 40C), cold winters (-20 to 10C), grass cover more dominant, tree cover proportional in part to rainfall, precipitation less than deciduous forest (30 to 90 cm)



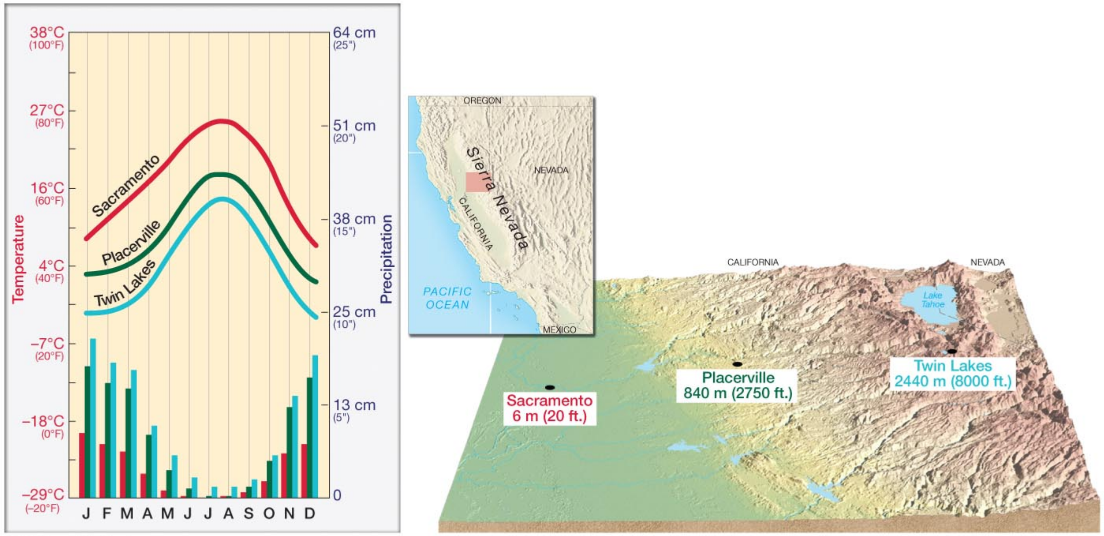
Climates of the world: continental deserts

- Hot summers (average high temperatures often above 35 C), cold to mild winters, large diurnal temperature contrast, limited vegetation primarily near sources of water, very arid (less than 30 cm of rainfall)



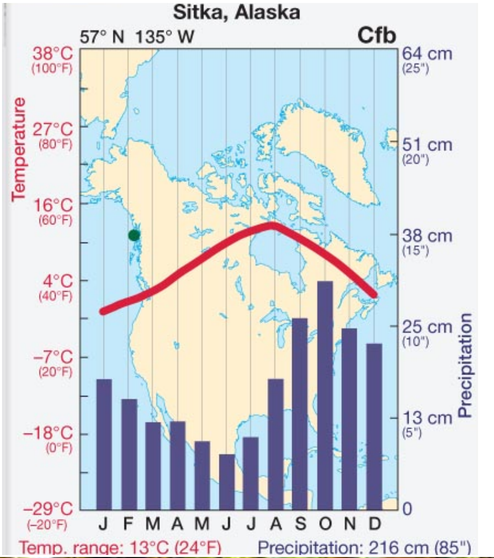
Climates of the world: highland climates

- Generally colder and more abundant precipitation than surroundings



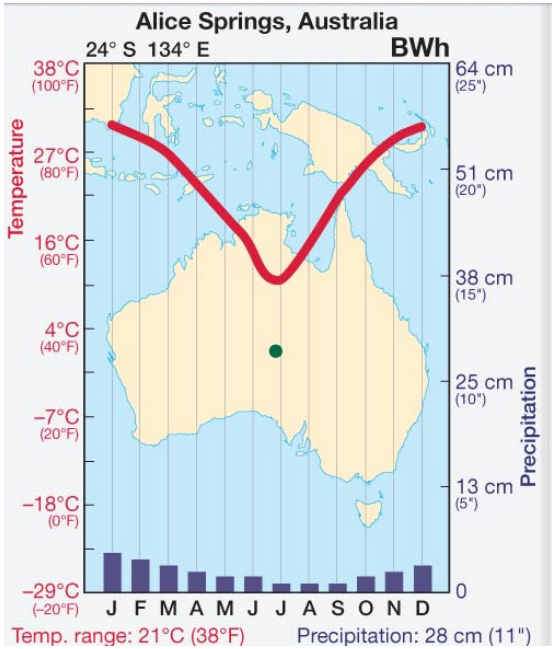
Climates of the world: midlatitude marine climates/rain forests

- Relatively limited temperature variability (comparatively cool summers (15 to 25C) and warm winters (0 to 15 C), usually trees are mostly conifers, very abundant rainfall (160 cm+)



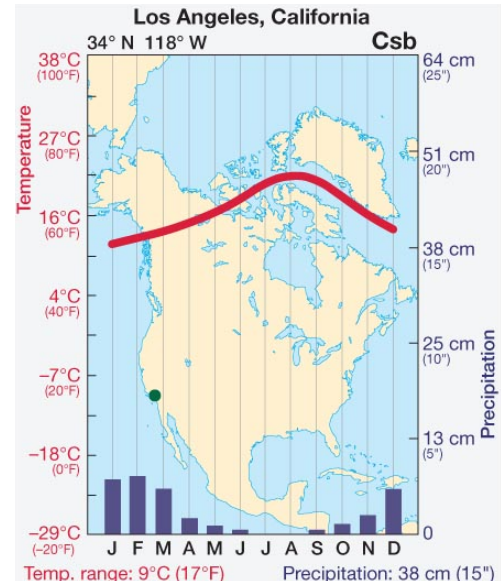
Climates of the world: tropical/ subtropical deserts

- Very hot summers (summer time highs often above 40C), cool to cold winters (0-15C), large diurnal temperature range, very arid (less than 20 cm rainfall)



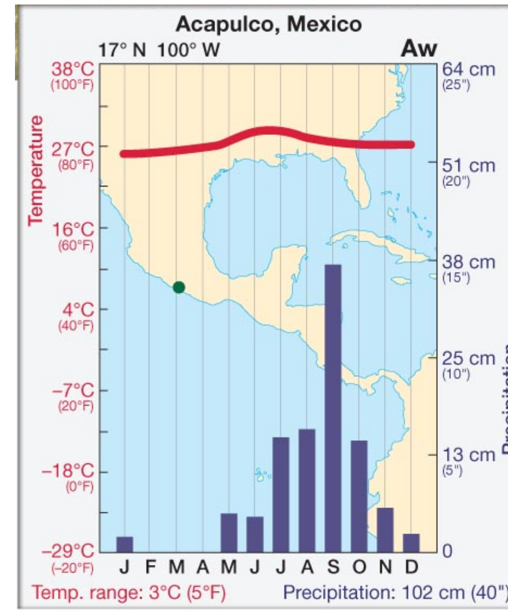
Climates of the world: Mediterranean/scrub climates

- Hot (35 C+) dry summers, cool to mild (0-15C), wet winters, generally semi-arid climatology (rainfall less than 50cm, except at higher elevations)



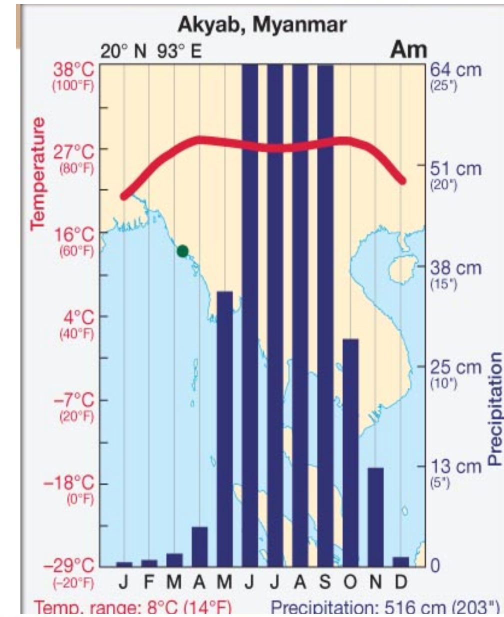
Climates of the world: semi-arid tropical climates

- Savannah – tropical grassland; tree and grass cover vary with precipitation; warm to hot all year round (high temperatures rarely below 25 C and lows rarely below 10C) pronounced wet-dry seasonality depending on the position of the intertropical convergence zone (average precipitation ranges from 20 to 90 cm)



Climates of the world: tropical wet-dry forests

- Similar temperatures and seasonality to semi-arid tropical climates, but more abundant rainfall (90 to 160 cm), the highest temperatures are usually a little cooler than in the arid and semi-arid environments
- In drier forests, trees may be deciduous on a precipitation basis, but in wet forests, broadleaf trees can exist year round
- It should be noted that there are some extremely wet places in the tropics that still have a very strongly monsoonal wet/dry seasonality to their rainfall



Climates of the world: tropical rain forests

- Very stable, warm to hot temperatures all year round (around 30C high temperatures and 20-25C low temperatures), very abundant precipitation (160 cm +)
- The wettest places in the world are in the rainforest
- Very lush vegetation