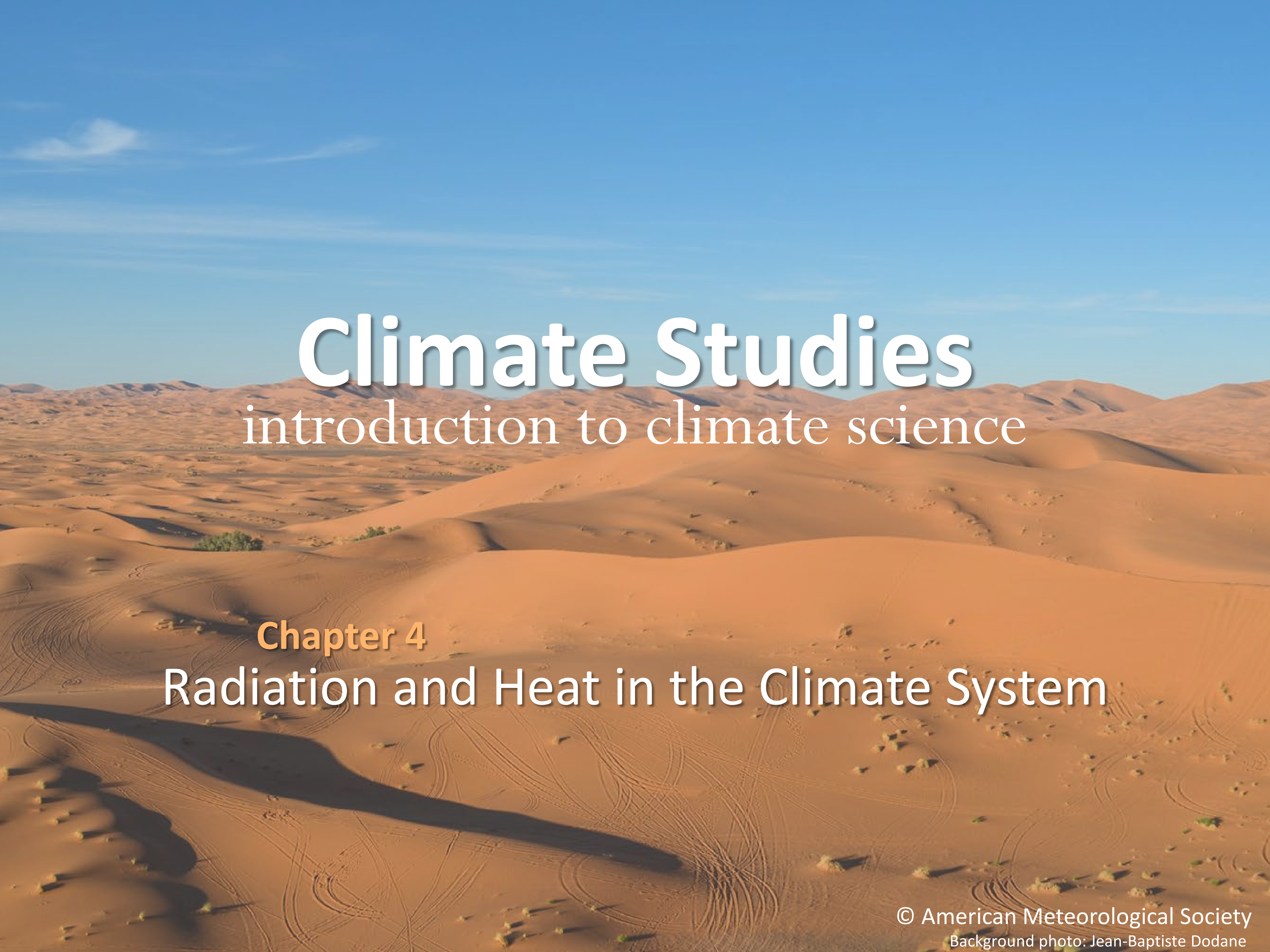


Climate Studies

introduction to climate science

Chapter 4

Radiation and Heat in the Climate System

Essential Questions

- How is energy defined?
- Why is radiative energy important to the climate system?
- What are the basic radiation laws that relate to the climate system?
- How do principles of radiation relate to the greenhouse effect?
- Why is the greenhouse effect necessary for life, yet of concern in terms of climate change?
- What can happen to solar radiation as it passes through the atmosphere?
- How do the astronomical positions of Earth and Sun contribute to the climatic seasons?
- Why is it important to measure and quantify the amount of heat in the climate system?
- By what mechanisms is energy transferred within the climate system?
- What are the major controls on climate?

Radiation and Heat in the Climate System

- Climate sciences rely upon the application of the fundamental laws of physics and chemistry to model and explain the energy interactions between the climate sub-systems
- We embark on a thorough examination of those laws of physics that directly apply to our understanding of the climate system
  - For more accuracy in asserting the certainties and uncertainties in climatic processes
  - To make better decisions for society that lessen our vulnerability to changes in climate

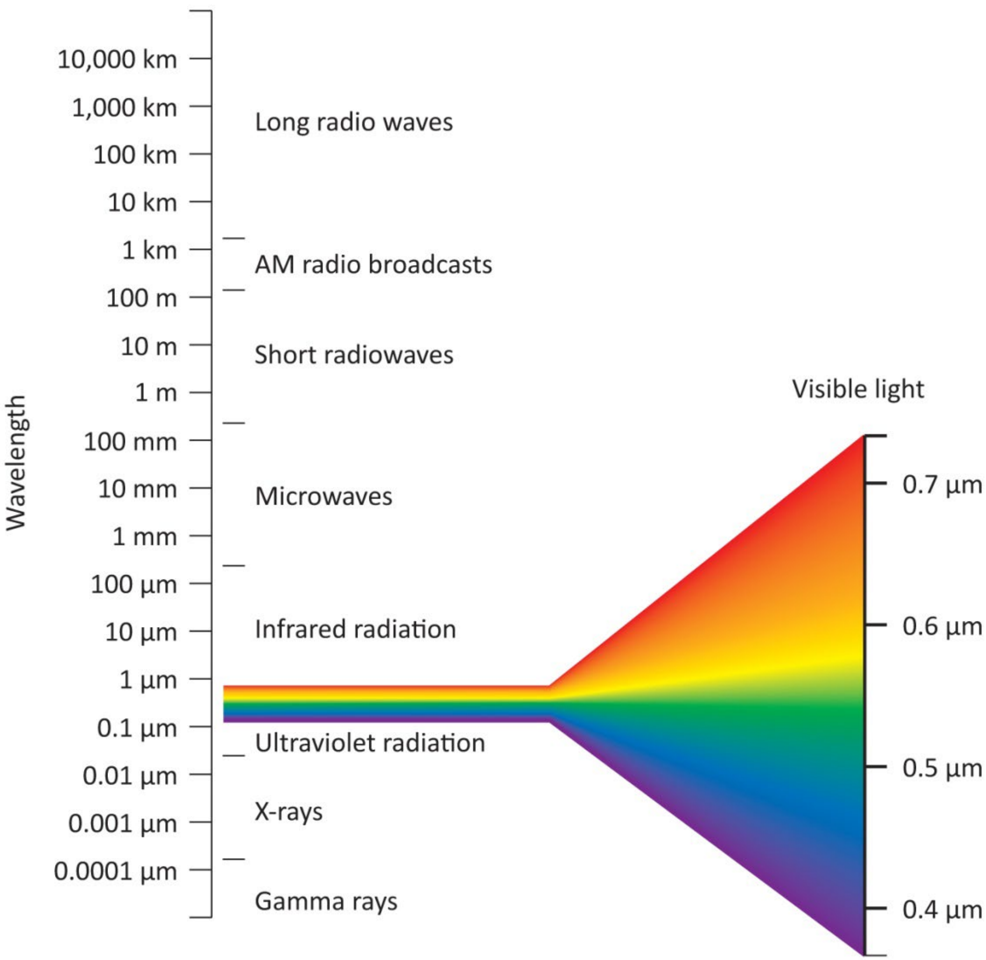
Radiation and Heat in the Climate System

- The journey begins with focusing on energy received from the Sun
  - Energy is received, absorbed, transferred and re-emitted to space
  - Transformed mainly to heat, it works to define unique climatic characteristics on Earth
- We trace the ways in which energy works its way through the various sub-systems in climate. It is important to first precisely define what energy is and why it is important.

Energy & Entropy

- **Energy** - capacity for doing work, occurring in many forms, including radiation and heat
  - ultimate source of energy for our planet's climate system and its sub-systems is the Sun
- **Entropy** – capacity for chaos (measure of disorder)
- *1st law of thermodynamics* (**law of conservation of energy**) – the form of energy can be changed but it cannot be created or destroyed
- **2nd law of thermodynamics** – energy flows from regions of higher concentration to regions of lower concentration

Type of Radiation



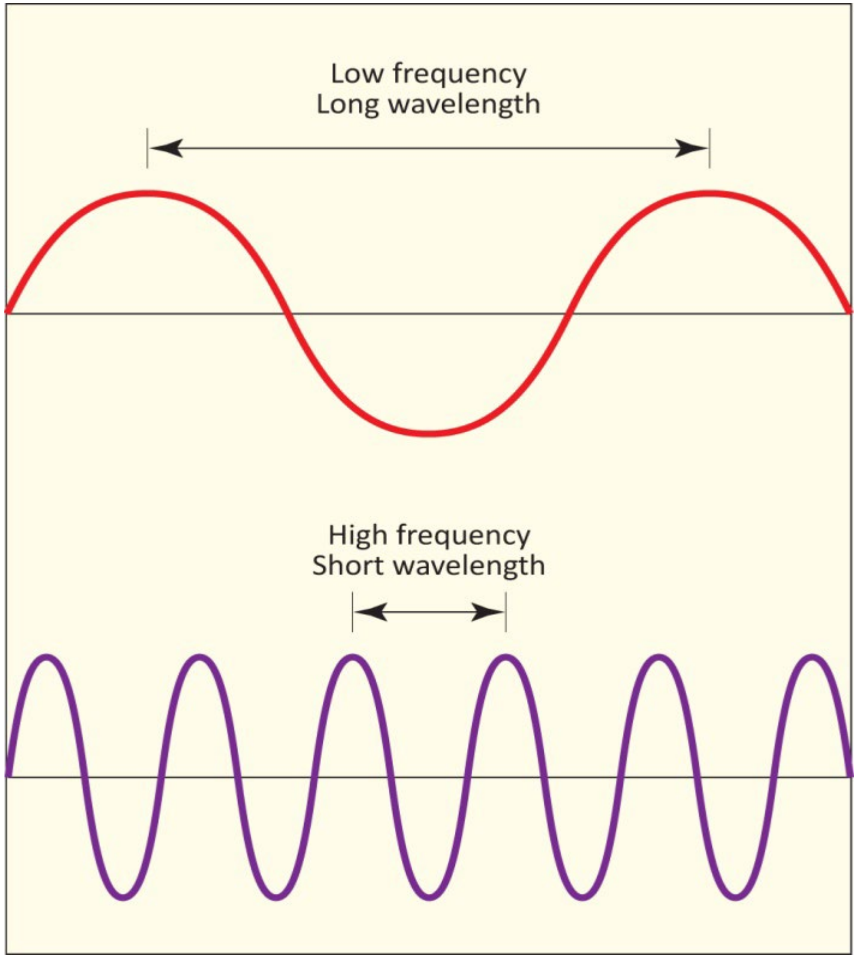
- **Electromagnetic spectrum** – devised to differentiate the varying properties of these waves according to wavelengths
- **Visible radiation** – only segment of the spectrum perceptible to the human eye
- **Infrared (IR) radiation** – with decreasing energy and longer wavelengths, commonly connected to heating of the atmosphere

Type of Radiation

- **Wavelength** (λ) – distance between either a wave ridge (top) or trough (bottom) to the next succeeding ridge or trough, respectively.
- **Frequency** (*f*) the number of wavelengths passing a point in a unit of time.

$$c = f\lambda$$

c = speed of light (3×10^8 m/s)



Radiation Principles

- **Blackbody -** a perfect absorber and a perfect emitter of radiation that emits the maximum amount of radiation and absorbs all the radiation reaching it
  - wavelength of most intense radiation emitted by a blackbody is inversely proportional to the absolute temperature of the object

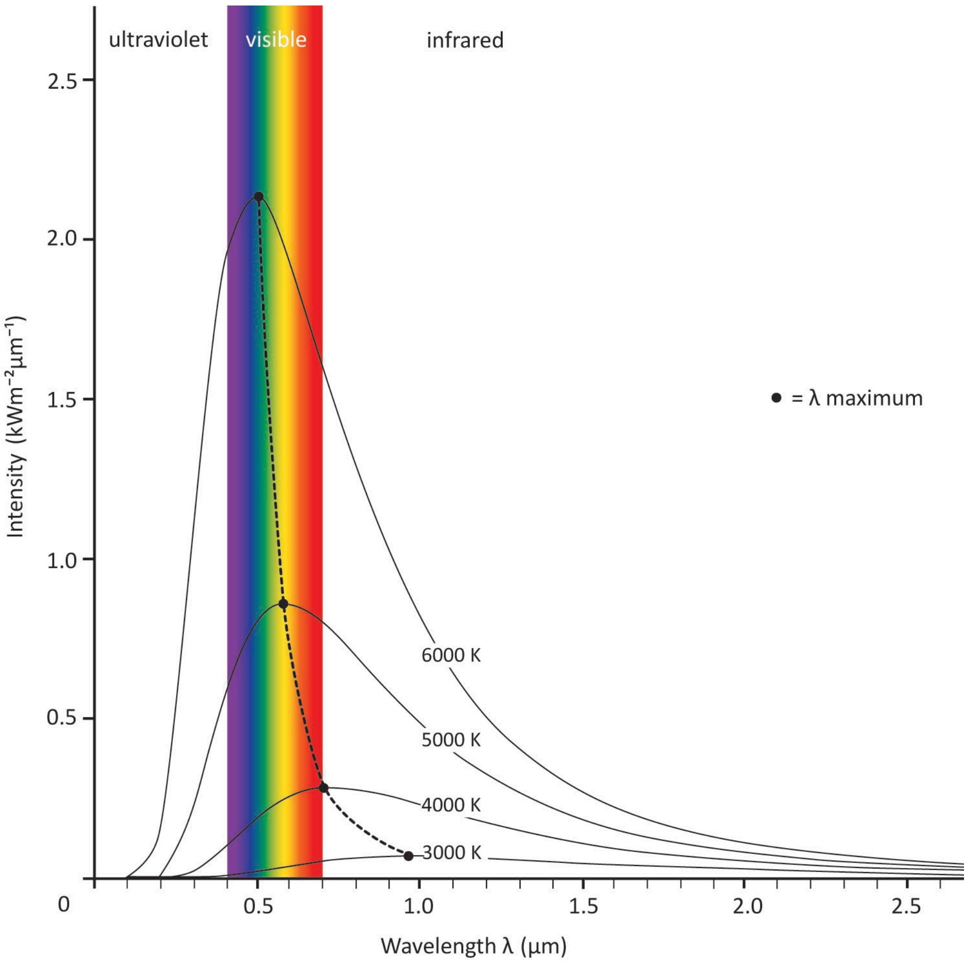
$\lambda_{max} = C/T$

λ_{max} = wavelength of most intense radiation (μm)

C = constant of proportionality = 2897

T = absolute temperature (K)

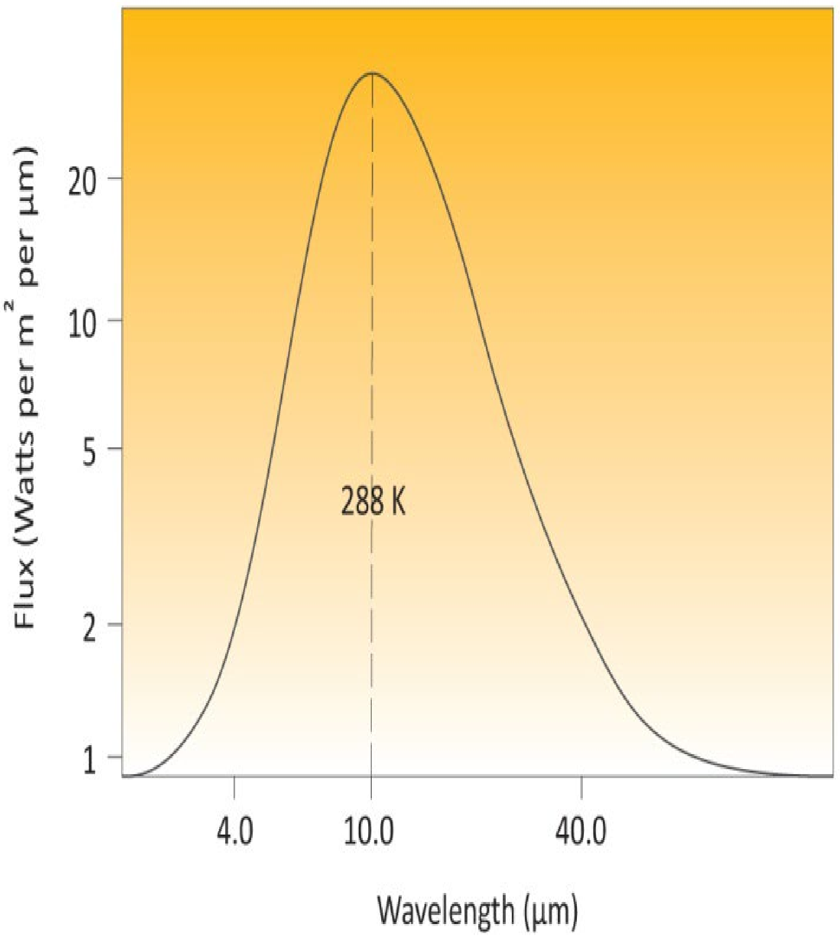
Radiation Principles



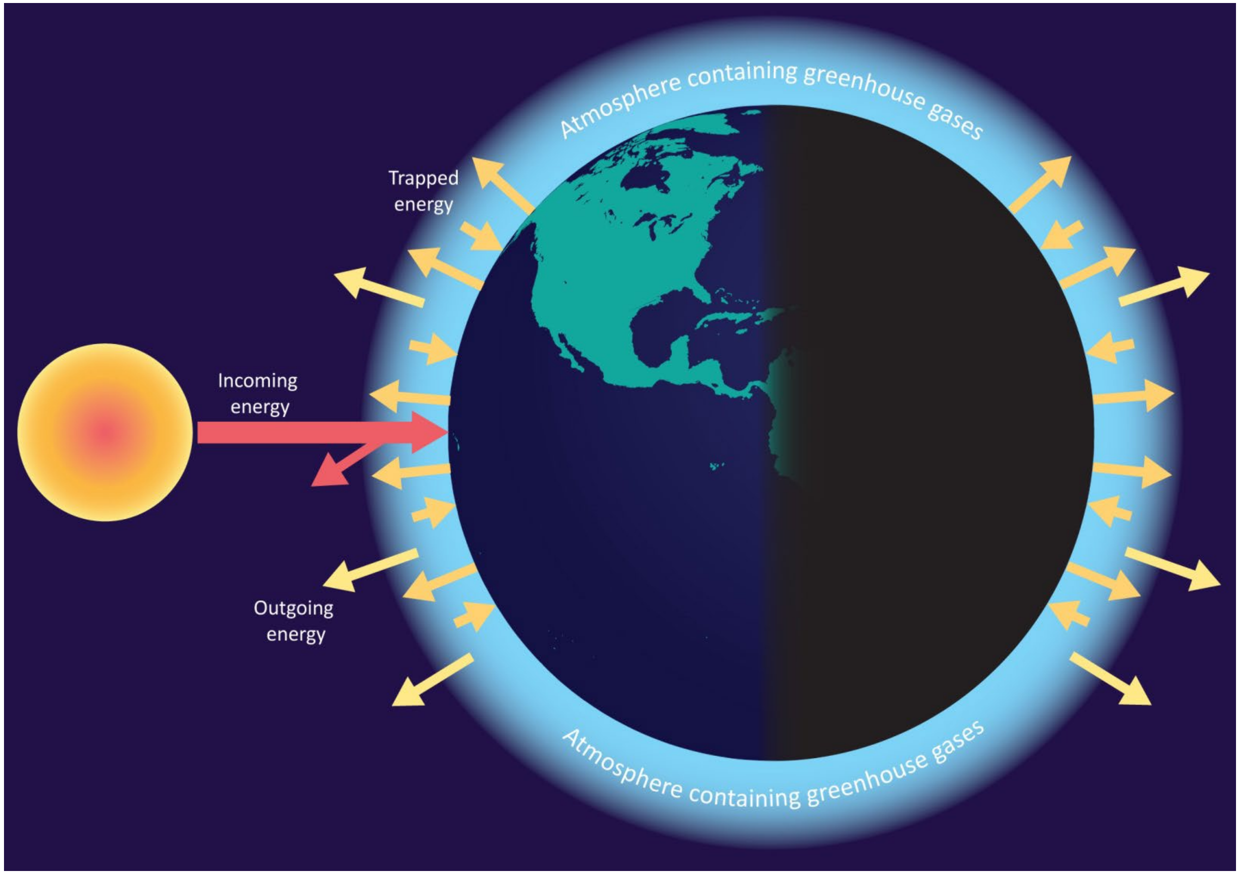
- **Wien's displacement law** - physical relationship of which the wavelength of an object emits its maximum amount of radiative energy
  - As an object's temperature rises, this peak intensity shifts to a shorter-wavelength
  - As the surface temperature decreases, the peak intensity shifts to a longer-wavelength

Radiation Principles

- **Stefan-Boltzmann Law -** the total energy flux emitted by a blackbody across all wavelengths is proportional to the fourth power of the absolute temperature of the object
  - hot objects, such as the Sun, emit peak radiation at short wavelengths
  - cold objects, such as Earth, emit peak radiation at longer wavelengths



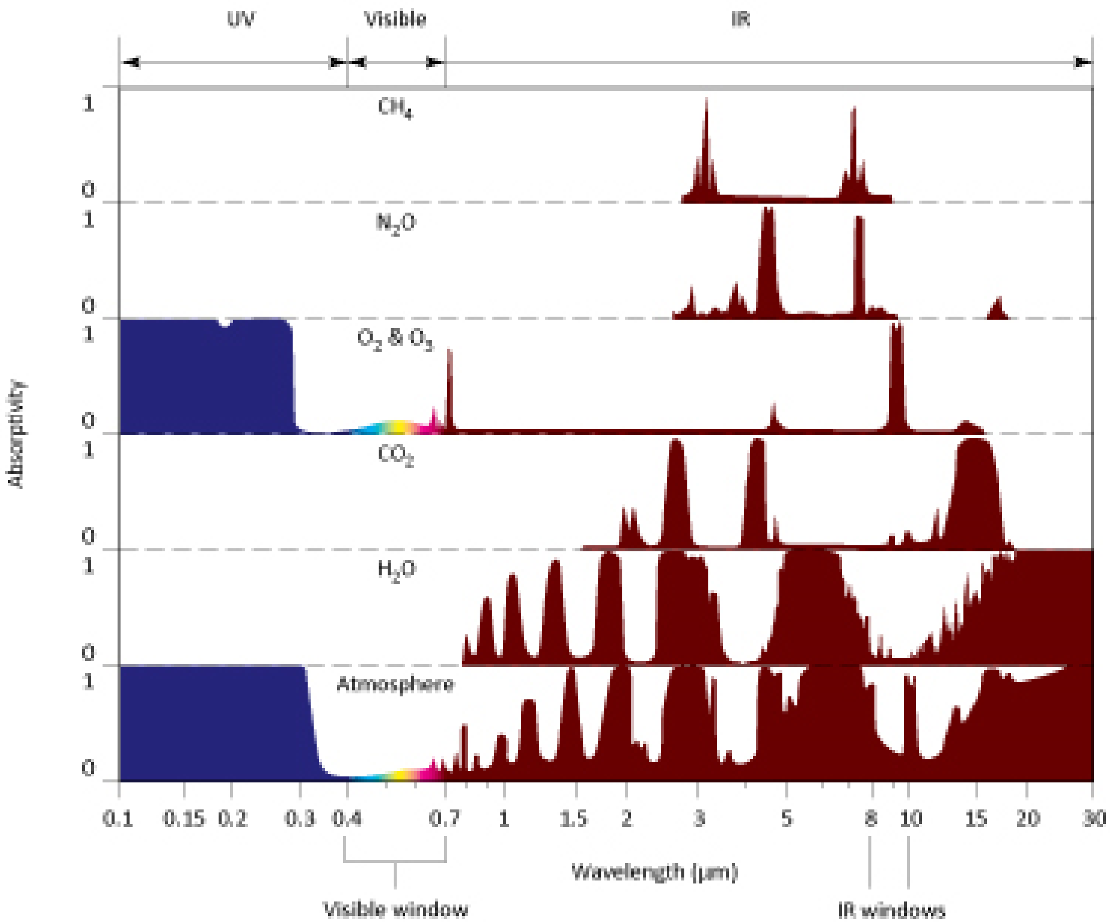
Global Radiative Equilibrium and Greenhouse Effect



- **Global Radiative Equilibrium -** outgoing emission of heat (infrared radiation) to space balances the incoming solar radiation
- **Greenhouse effect -** heating of Earth's surface and lower atmosphere by the absorption and emission of infrared radiation by greenhouse gases

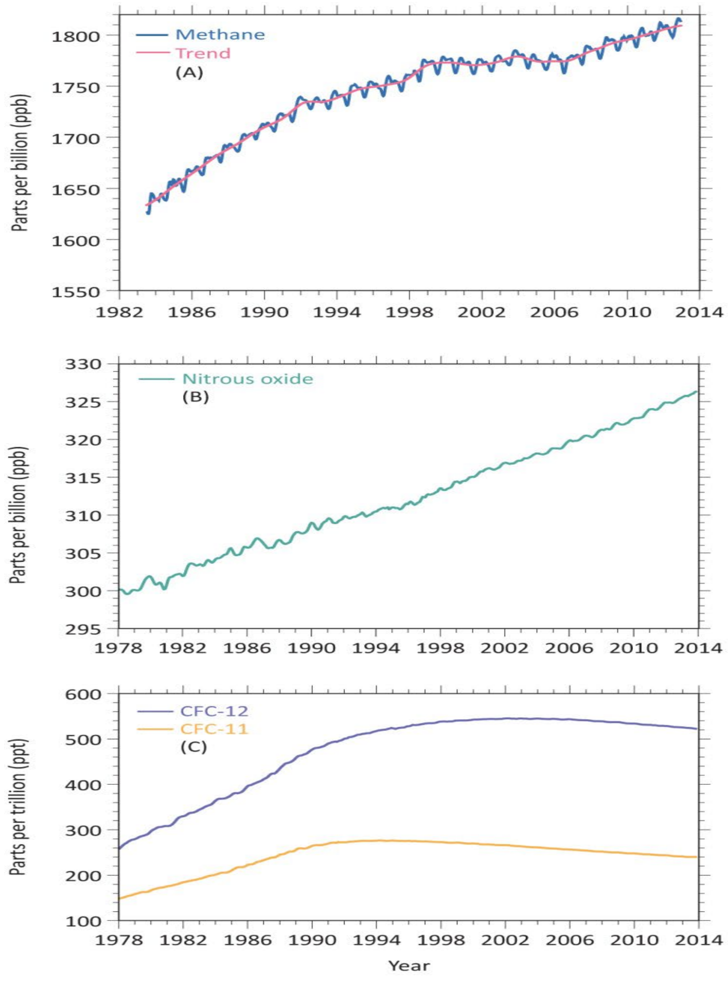
Greenhouse Effect

- Without the greenhouse effect, Earth would be too cold to support life
- Principal greenhouse gases
  - water vapor (49-71%)
  - carbon dioxide (22-29%)
  - ozone (7-8%)
  - methane (4-9%)



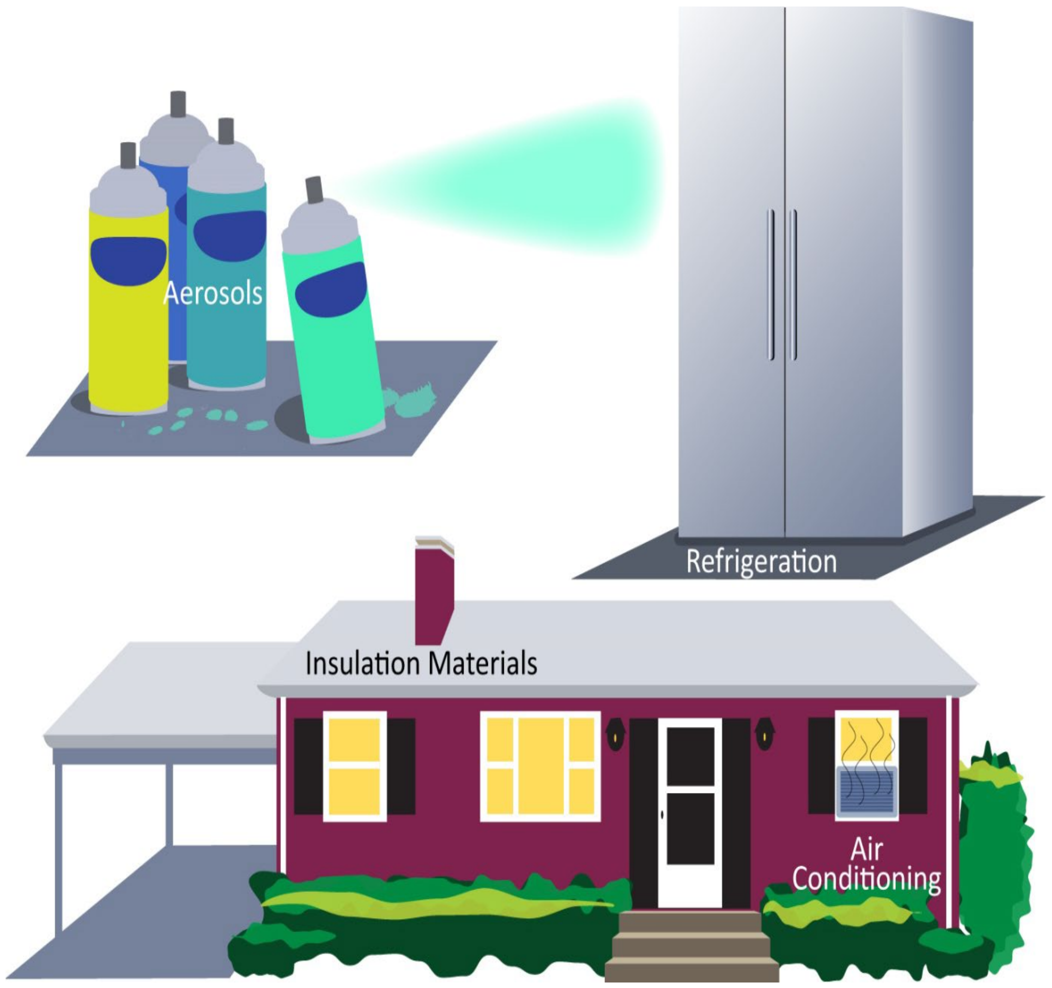
Global Warming

- Water vapor doesn't initiate new trends in climate, it amplifies trends
- **Industrial Revolution**
  - Began in the mid-18th century
  - Production methods changed to a more energy consuming, mechanized process
  - Depended on coal and oil that produced CO_2
- **Global warming –** increase in the magnitude of the greenhouse effect due to rise of CO_2, causes an increase to surface temperatures



- Methane (CH_4)
  - Product of anaerobic decay (decay in the absence of oxygen)
  - Emitted by cultivation of rice, raising cattle, landfills, termites, coal mining, wastewater treatment, and petroleum systems
- Nitrous oxide (N_2O)
  - Released from fossil fuel combustion, fertilizers and production of nitric acid
  - Nature accounts for more than 60%

- **Chlorofluorocarbons - **(CFCs) unique, synthetic gases used as refrigerants, propellants in aerosol sprays, and solvents



Global Warming

- **Global warming potential** (GWP) provides perspective on the importance of the various gases
- According to the U.S. Environmental Protection Agency (EPA), the "GWP for a particular greenhouse gas is the ratio of heat 'trapped' by one unit mass of the greenhouse gas to that of one unit mass of CO_2 over a specified time period"
  - Methane is 21 times more effective at trapping heat than CO_2 over 100 years
  - Nitrous oxide is 310 times more effective than CO_2 over 100 years
  - CO_2 has a much longer lifetime in the atmosphere

Global Radiation Budget

- Only solar radiation that is not scattered or reflected back to space, or absorbed by the atmosphere, reaches Earth's surface
- The percent of solar radiation that is absorbed (*absorptivity*) plus the percent scattered or reflected plus the percent transmitted to Earth's surface (*transmissivity*) must equal 100%, demonstrating the *law of conservation of energy*

Solar Radiation Traversing the Atmosphere

- **Scatter -** solar radiation dispersing forward, backward and sideways after hitting a particle
- **Reflection -** special case of scattering at the interface between two different media, such as air and cloud, when the solar radiation striking that interface is redirected
- **Albedo -** fraction of radiation redirected (reflected) by an interface

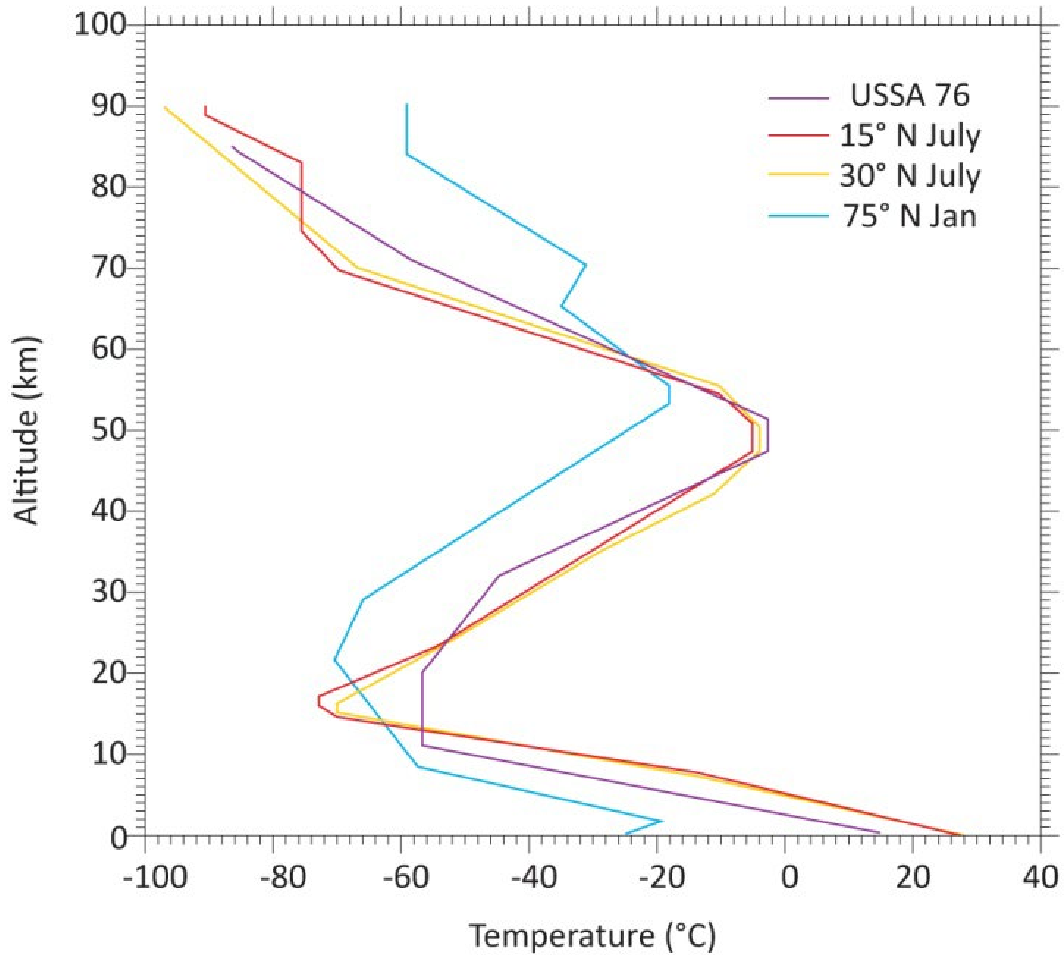
  albedo = (reflected radiation)/(incident radiation)
- **Earth's planetary albedo -** average of 31% of solar radiation reaching Earth that is scattered or reflected back to space

Solar Radiation Traversing the Atmosphere

Earth's Solar Radiation Budget	
Reflected by the Earth-atmosphere system	31%
Absorbed by the atmosphere	20%
Absorbed by Earth's surface	49%
Total	100%

Solar Radiation Traversing the Atmosphere

- Infrared radiation, emitted by Earth's surface, warms the atmosphere
- The air closest to Earth's surface is the warmest, and the temperature drops as altitude increases in the troposphere



Solar Radiation Traversing the Atmosphere

- Solar radiation striking clouds is reflected
  - Thin clouds (less than 50 m or 165 ft.) have an albedo of 40%
  - Thick clouds (more than 5000 m or 16,500 ft.) have an albedo of 80% or more
- Overall, average albedo for clouds is 55%
- Clouds, on average, cover 60% of the planet

Solar Radiation Traversing the Atmosphere

- **Absorption -** selectively converts solar radiation into heat energy
  - Oxygen, ozone, water vapor and aerosols absorb solar radiation by wavelength
  - At specific wavelengths, they remove entire bands before solar radiation reaches Earth's surface

Stratospheric Ozone Shield

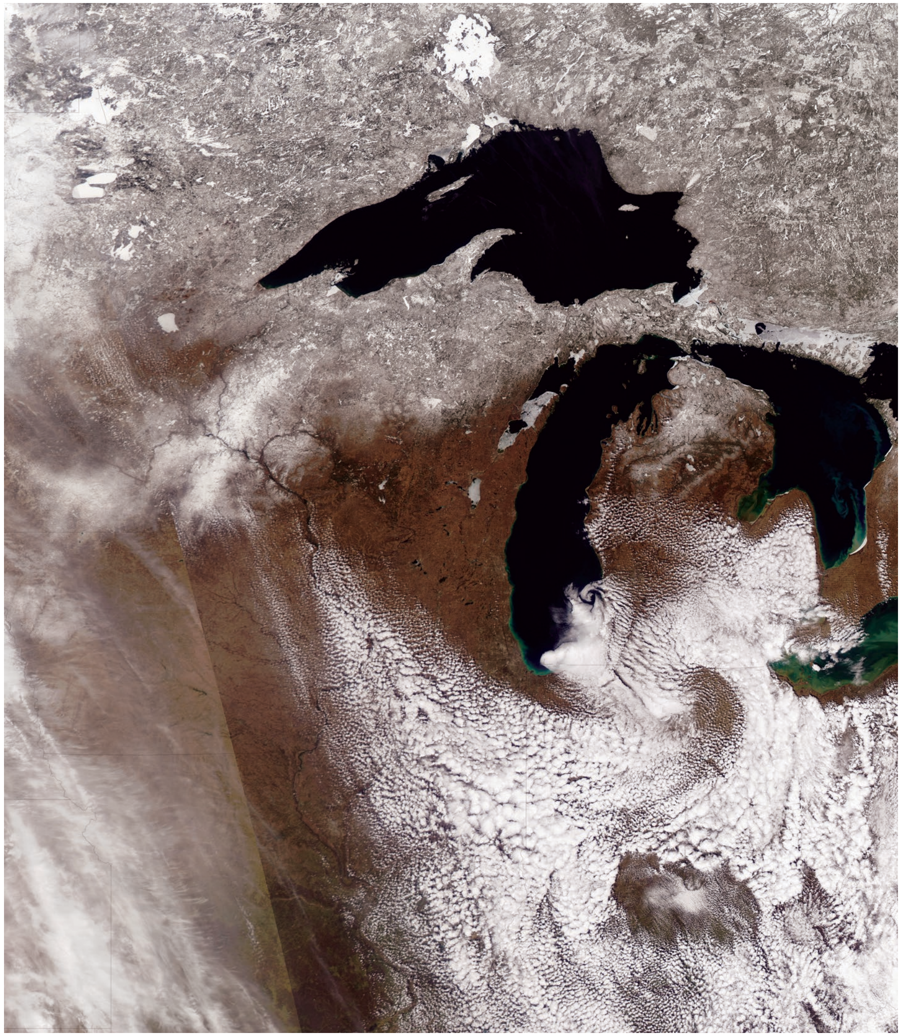
- **Stratospheric ozone shield -** where the generation and dissociation of ozone by UV radiation heats the stratosphere
  - O_3 absorbs UV radiation, splitting into O and O_2
    - Then O collides with O_3 creating two O_2
  - UV radiation strikes O_2, splits it into two O
    - Then O collides with O_2 to form O_3

Earth's Surface and Solar Radiation

Surface	Albedo (% reflected)
Deciduous forest	15-18
Coniferous forest	9-15
Tropical rainforest	7-15
Tundra	15-35
Grasslands	18-25
Desert	25-30
Sand	30-35
Soil	5-30
Green crops	15-25
Sea ice	30-40

Surface	Albedo (% reflected)
Fresh snow	75-95
Old snow	40-60
Glacial ice	20-40
Water body (high solar altitude)	3-10
Water body (low solar altitude)	10-100
Asphalt road	5-10
Urban area	14-18
Cumulonimbus cloud	90
Stratocumulus cloud	60
Cirrus cloud	40-50

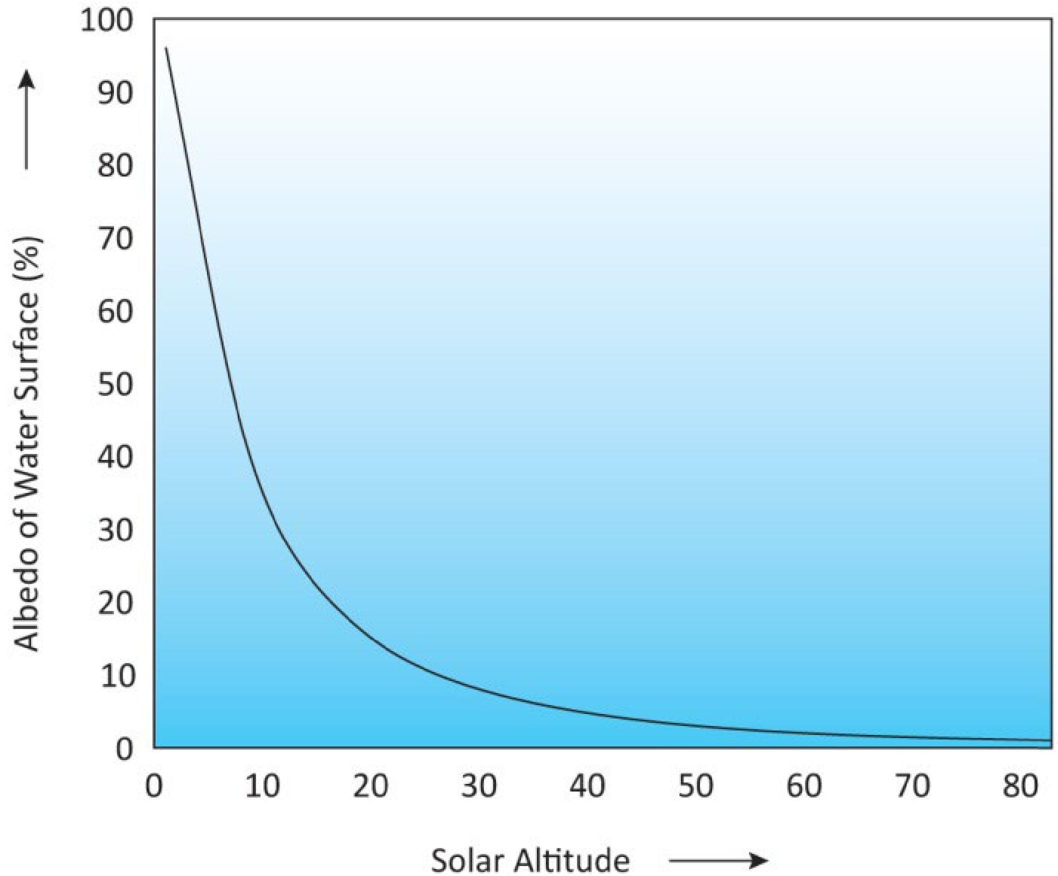
Earth's Surface and Solar Radiation



- Unlike snow, the lakes appear dark because of their low albedo and strong absorption of solar radiation

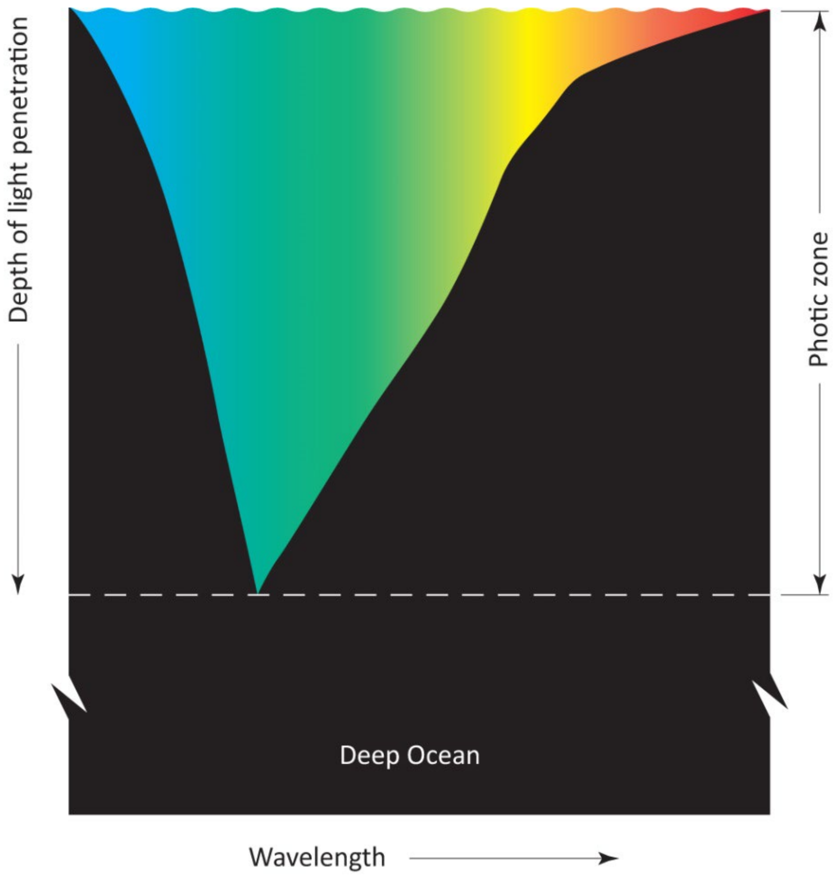
Earth’s Surface and Solar Radiation

- Albedo varies with the *solar altitude*, the angle of the Sun above the horizon
- Under clear skies, the albedo of flat, tranquil water decreases with increasing solar altitude

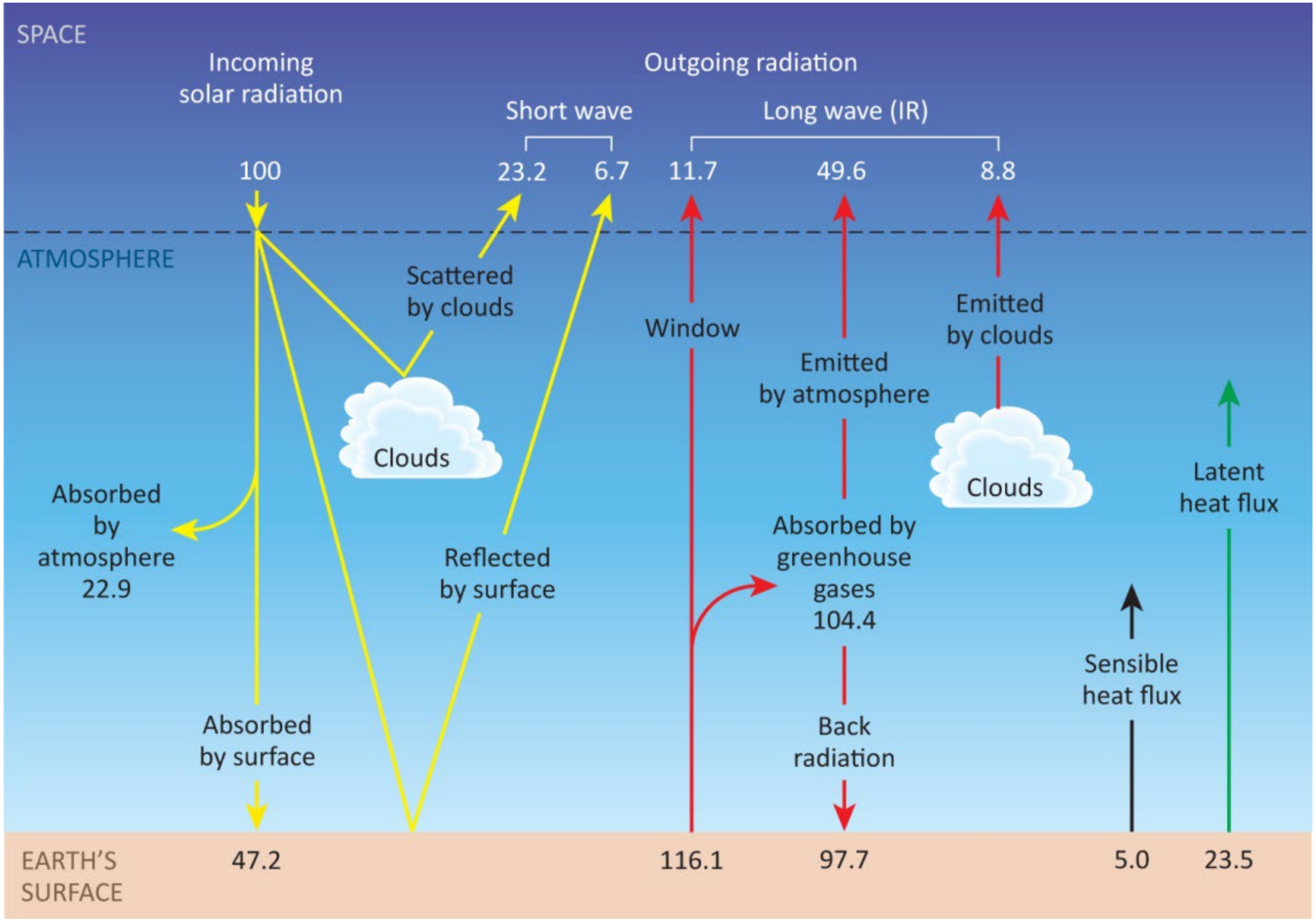


Earth's Surface and Solar Radiation

- Longer wavelengths, reds and yellows, are absorbed more efficiently than the shorter wavelengths, greens and blues
- In clear, clean water
  - Red light is completely absorbed within 15 m (50 ft.) of the surface
  - Green and blue-violet light penetrate to depths approaching 250 m (800 ft.)
  - More green and blue light scattered, giving the ocean its green-blue coloring
- Little sunlight reaches below 10 m (35 ft.) in near-shore waters
  - Murky waters receive color from the suspended particles preferentially scattering yellow and green light



Heat Imbalance: Earth's Atmosphere vs Earth's Surface



Global Radiative Balance

Global radiative balance	
Solar radiation intercepted by Earth	100 units
Solar radiation budget	
Scattered and reflected to space (23.2 + 6.7)	29.9
Absorbed by the atmosphere	22.9
Absorbed at the Earth's surface	47.2
Total	100 units
Radiation budget at the Earth's surface	
Infrared cooling (97.7 – 116.1)	-18.4
Solar heating	+47.2
Net heating	+28.8 units
Radiation budget of the atmosphere	
Infrared cooling (49.6 – 8.8 + 104.4 - 97.7)	-51.7
Solar heating	+22.9
Net cooling	-28.8 units
Non-radiative heat transfer: Earth's surface to atmosphere	
Sensible heating (conduction plus convection)	5.0
Latent heating (phase changes of water)	23.5
Net transfer	28.5 units

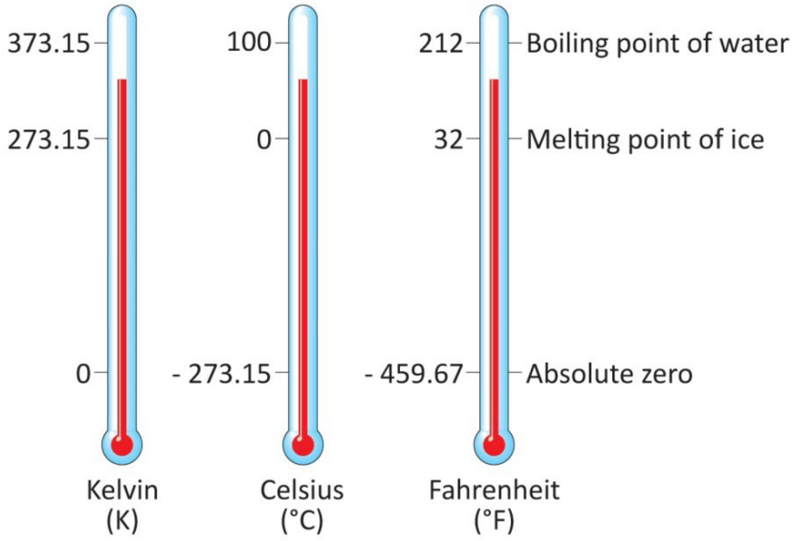
Thermal Energy Across Space and Time

- Differences in rates of radiational heating and cooling produce temperature gradients between Earth's surface and atmosphere, as well as between the tropics and higher latitudes
  - **Temperature gradient -** difference of temperature over a distance
- In response, heat is transported from Earth's surface to the atmosphere and from the tropics to higher latitudes via air mass exchange, storms and ocean circulation

Temperature and Heat

- **Temperature -** average quantity of kinetic energy, the energy of atoms in continual motion
- **Heat -** measure of energy that transfers from warm to cooler objects
- **Absolute zero -** the theoretical point at which kinetic energy stops
  - 0 K
  - −273.15 °C
  - −459.67 °F
- **Joule –** the unit for measuring nearly all kinds of energy, including heat:
  - $1\ J = 1\ (kg*m^2)/s^2$
  - 1 cal = 4.2 J

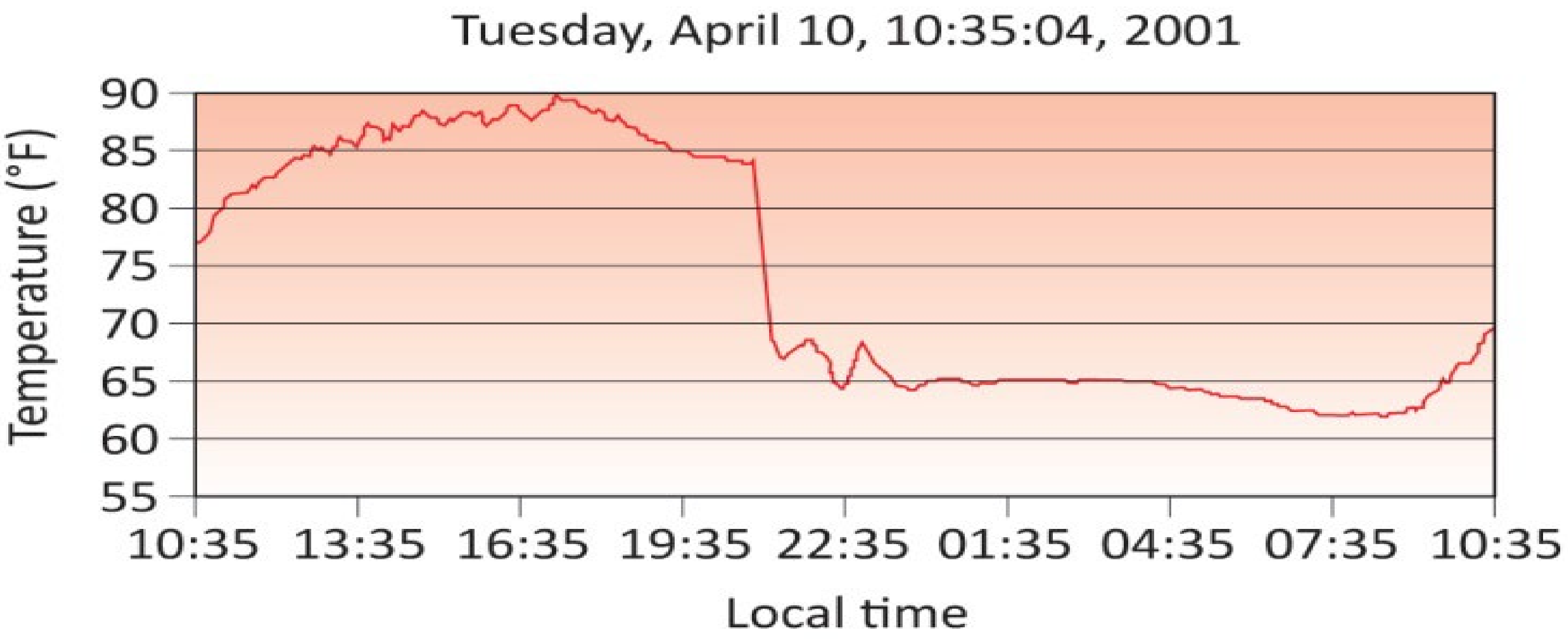
Temperature conversion	
°F	9/5 °C + 32°
°C	5/9 (°F + 32°)
K	5/9 (°F + 459.67)
K	°C + 273.15



Measuring Temperature

- **Thermometer -** a device that measures temperature, has been used since Galileo Galilei (1564-1642) invented a similar device in 1592
- A common thermometer consists of a liquid-in-glass tube attached to a graduated scale

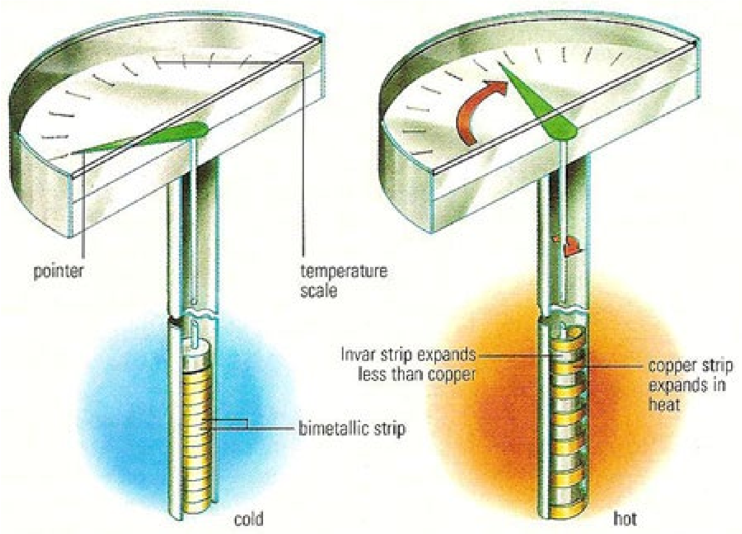
Measuring Temperature



- Electric thermometers are replacing manual, liquid-in-glass thermometers used by the NWS Cooperative Observation Network and the U.S. Automated Surface Observing System (ASOS)

Measuring Temperature

- *Bimetallic strip*
  - made of two metals welded back to back
  - Each metal has a different thermal expansion rate
    - One expands more than the other
    - The one that expands fastest bends about the one expanding less
  - Used in cooking applications, home thermostats or soil thermometers



Measuring Temperature

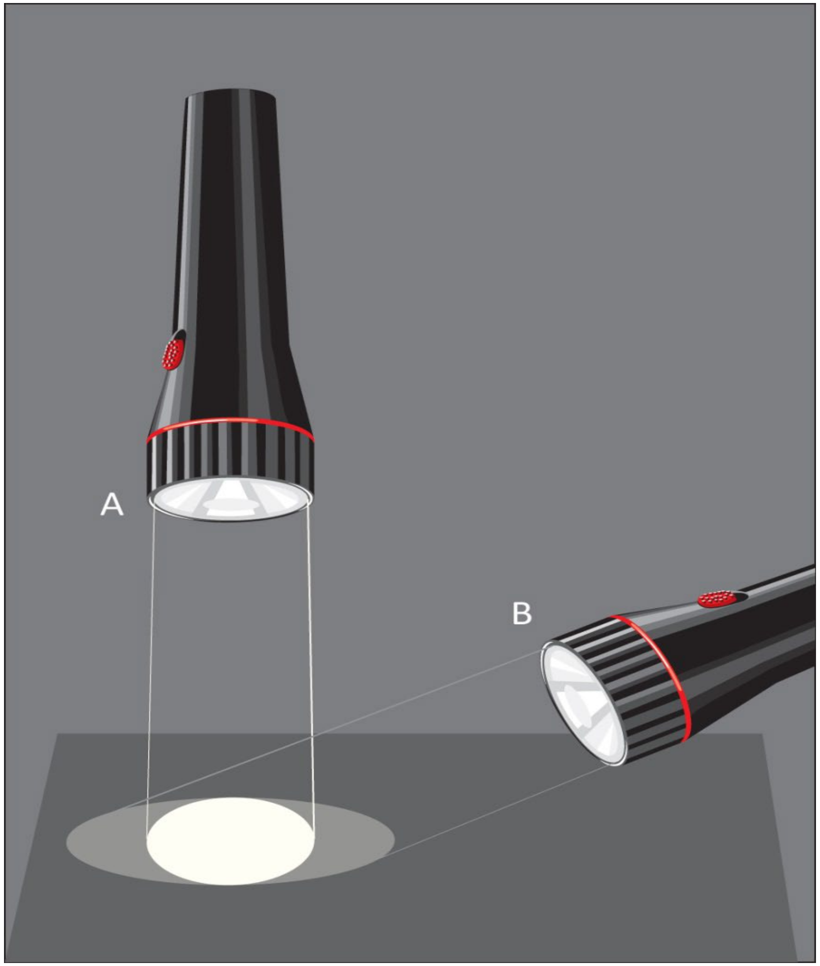
- White, louvered wooden shelter
  - Standard practice for official measurement for more than a century
  - Located in open grassy areas, well away from trees, buildings and other obstacles
  - Standard height of 1.5 m (5 ft.) about the ground
  - Ventilated white plastic enclosures are becoming more common

Energy Considerations for the Sun and Earth

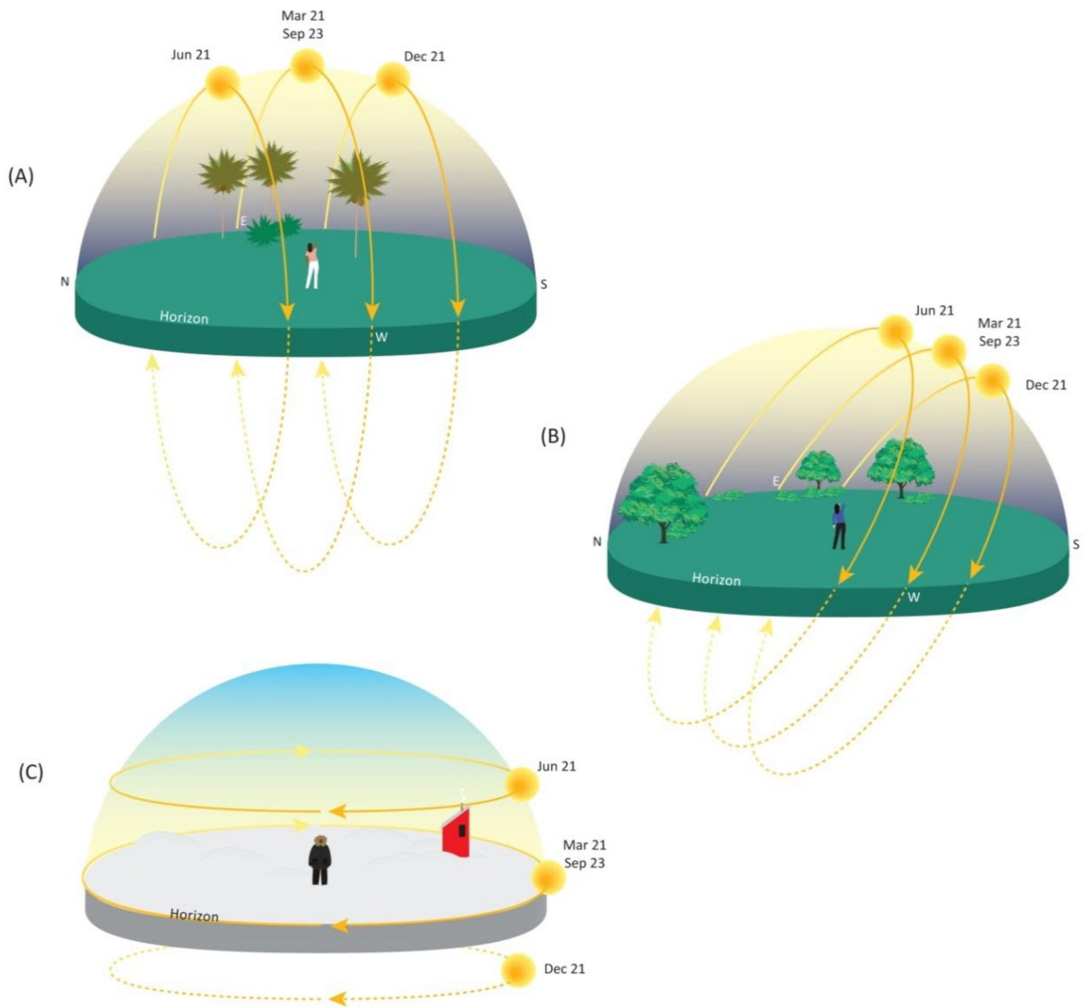
- **Circle of illumination –** the distinguishing line between day and night that circles the planet
- **Aphelion -** in July when Earth is furthest from the Sun in its elliptical orbit
- **Perihelion -** in January when Earth is closest to the Sun in its elliptical orbit

Changes in Solar Altitude

- **Solar altitude** – the angle of the Sun above the horizon, most commonly referenced at noon local time, each day's local maximum solar altitude.
  - (A) Whenever the Sun is directly overhead at its maximum angle of 90°, the solar rays are most concentrated
  - (B) When the Sun appears lower in the sky, the solar altitude is lower and solar radiation is spread over Earth's surface with less intensity

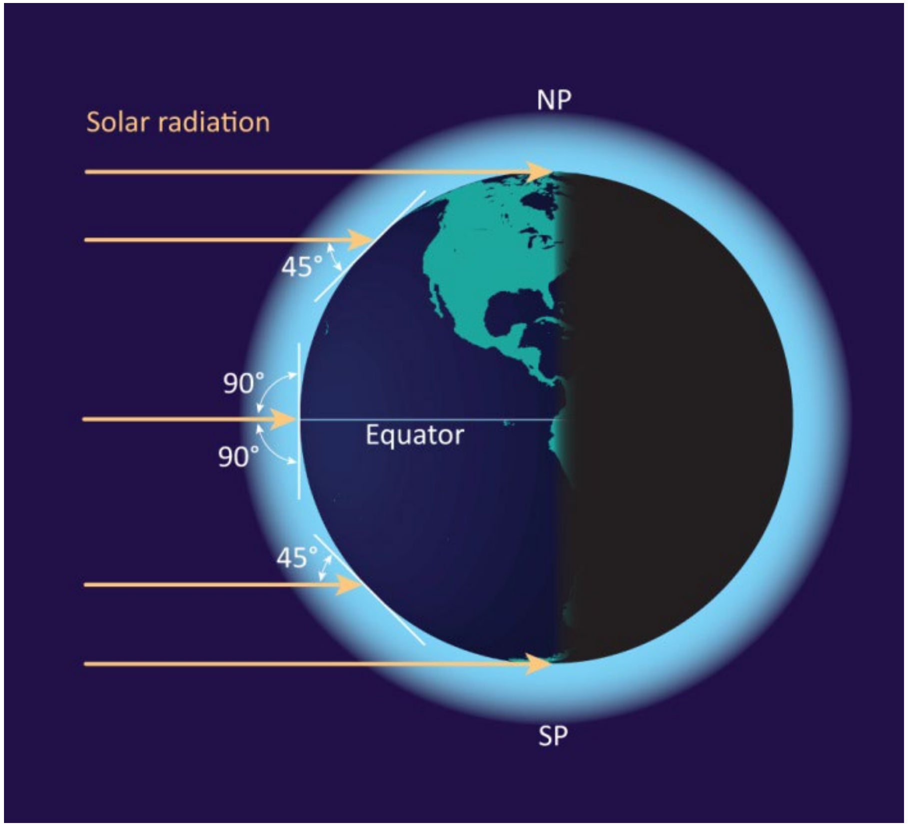


Changes in Solar Altitude



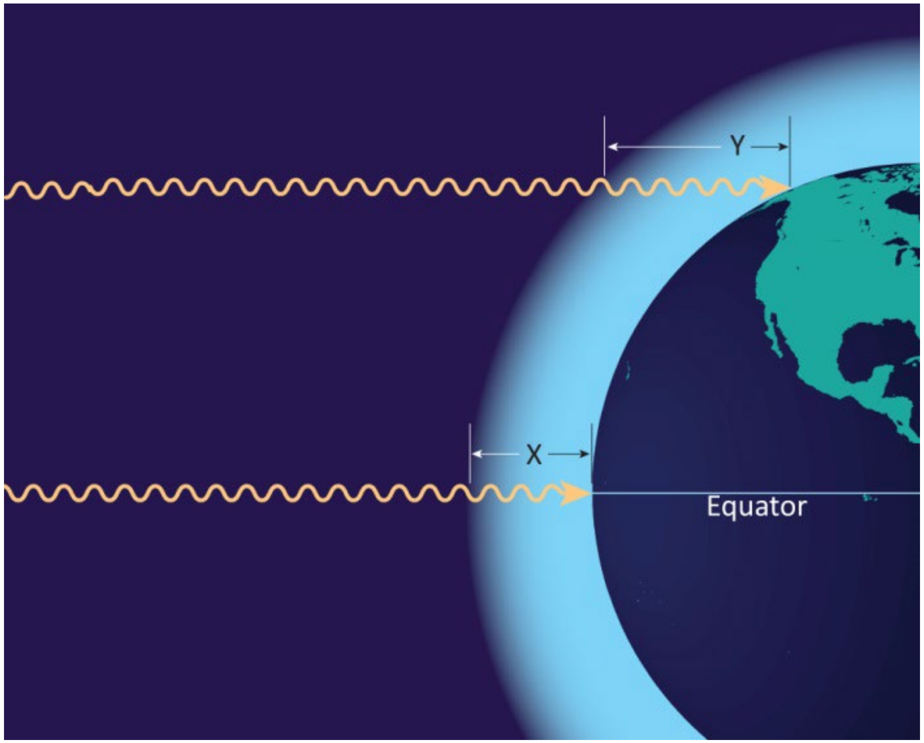
- Changes in solar altitude throughout the year impact seasonal changes
- Path of the Sun through the sky on the solstices and equinoxes at
  - (A) the equator
  - (B) middle latitudes of the Northern Hemisphere
  - (C) the North Pole

Changes in Solar Altitude



- Solar radiation reaches the planet as parallel beams with uniform intensity
- Earth's curved surface means that noon's solar altitude varies by latitude

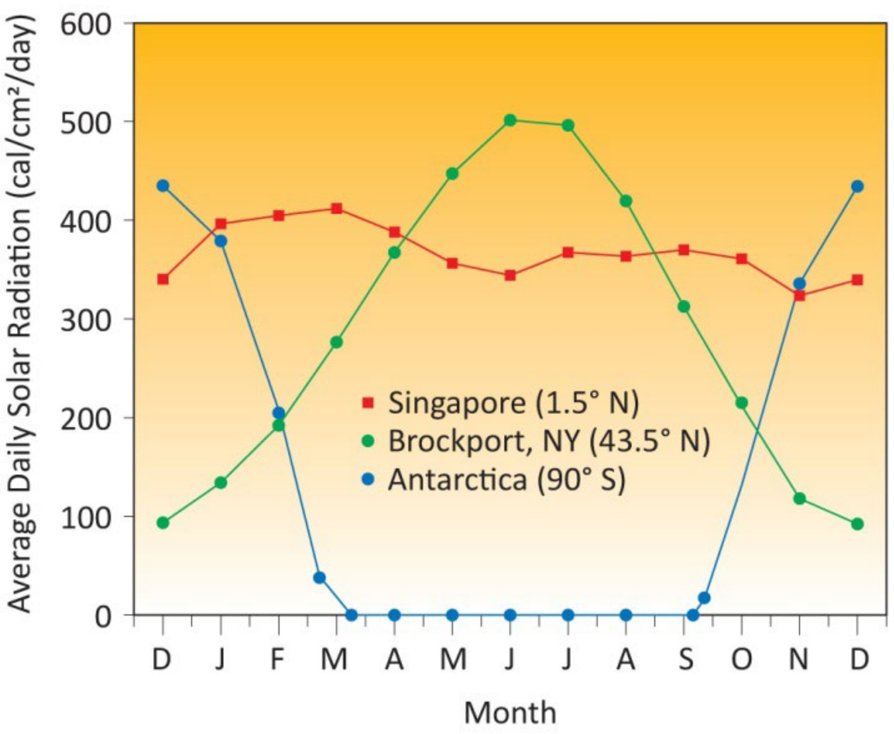
Changes in Solar Altitude



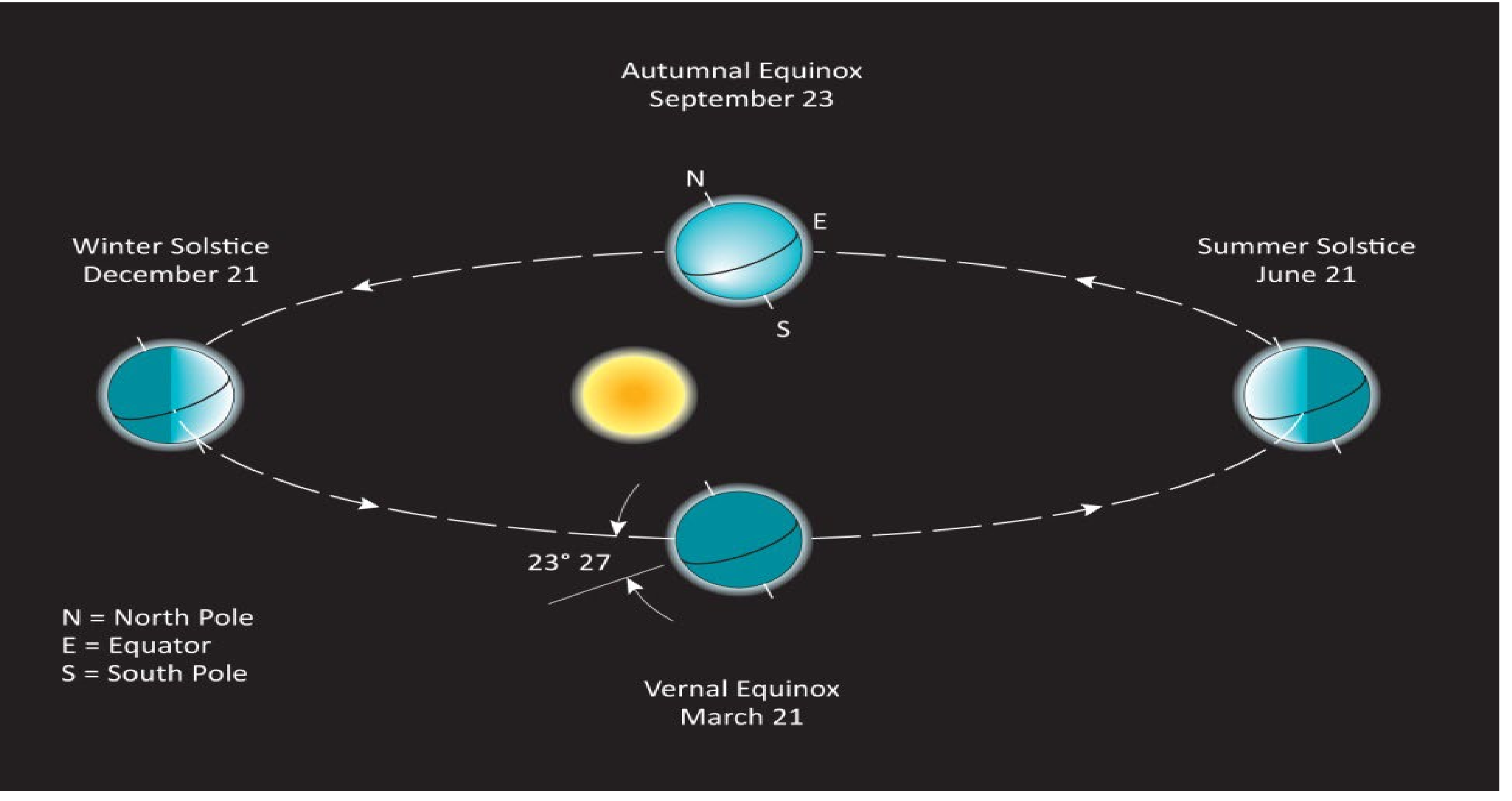
- The greater the solar altitude, the shorter the path solar radiation takes through the atmosphere
- Longer paths, at the lower solar altitudes, increase the amount of atmosphere for solar radiation to pass through and interact with clouds, gases and aerosols

Changes in Solar Altitude

- In the summer, days are warmer due to greater length of daylight, increasing the received solar radiation
- Both the length of daylight and solar altitude are major controls of the seasons
- In the tropics, with little variation in either length of day or noon solar altitude, the seasonal ranges in temperatures vary little



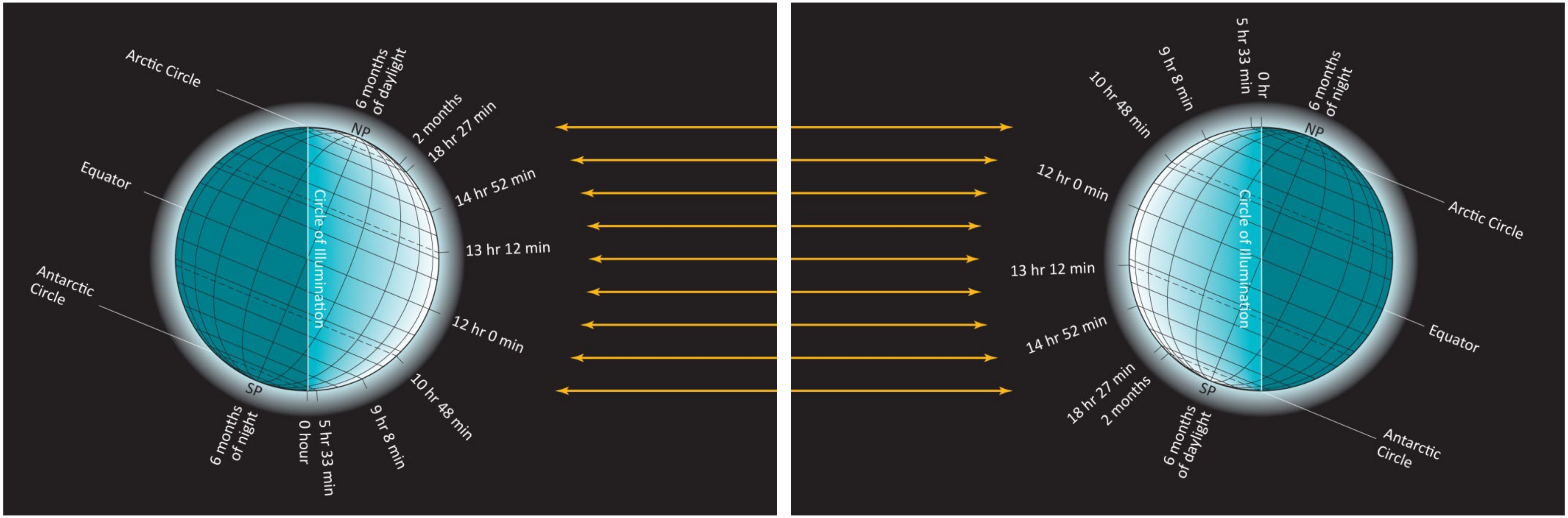
Earth's Revolution and the Seasons



Earth's Revolution and Seasons

- **Tropic of Cancer -** the farthest north the most intense radiation strikes the planet, at 23° 27' N of the equator
  - On or about 21 June
- **Tropic of Capricorn -** the farthest south the most intense radiation strikes the planet, at 23° 27' S of the equator
  - On or about 23 December
- **Solstice -** twice a year when the Sun reaches its maximum declination
  - (the Tropic of Cancer and Capricorn)
- **Arctic Circle -** 66° 33' N
  - Continuous daylight in June and night in December
- **Antarctic Circle -** 66° 33' S
  - Continuous daylight in December and night in June
- **Equinox -** local noon solar altitude is 90° over the equator
  - On or about 21 March and 23 September
  - Night and day are both 12 hours in the Northern and Southern Hemispheres

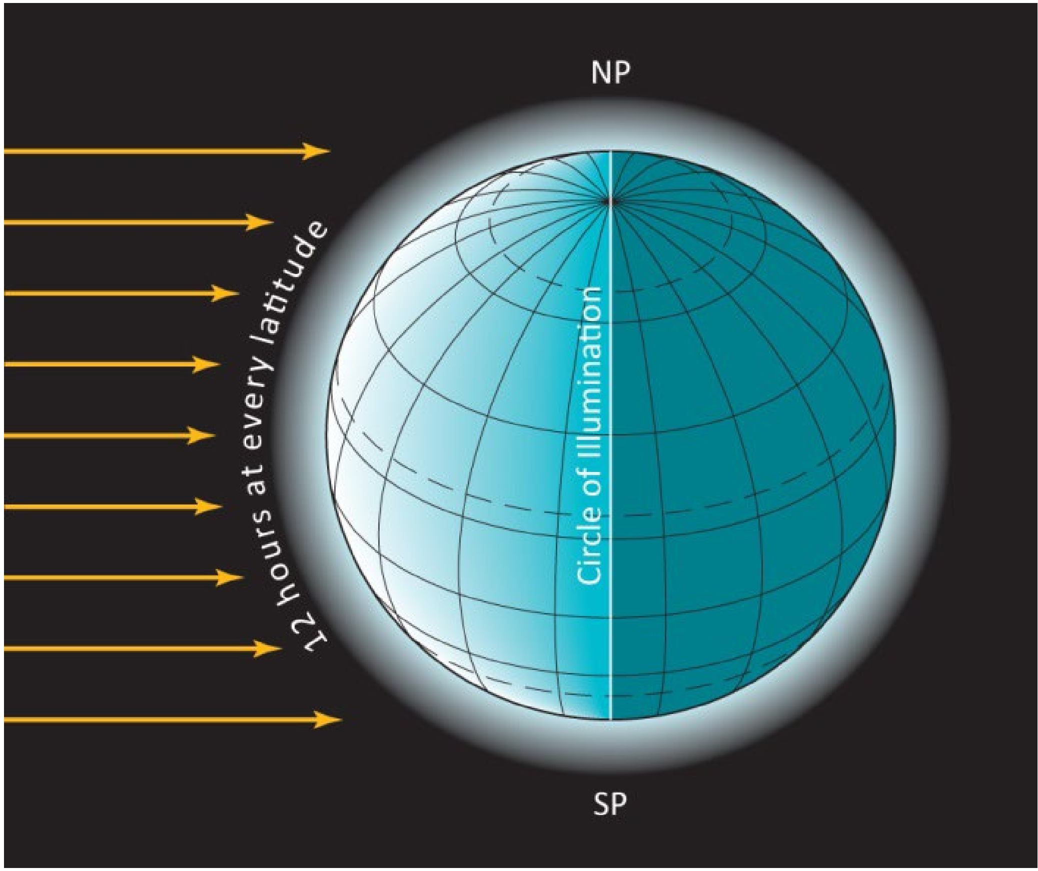
Earth’s Revolution and Seasons



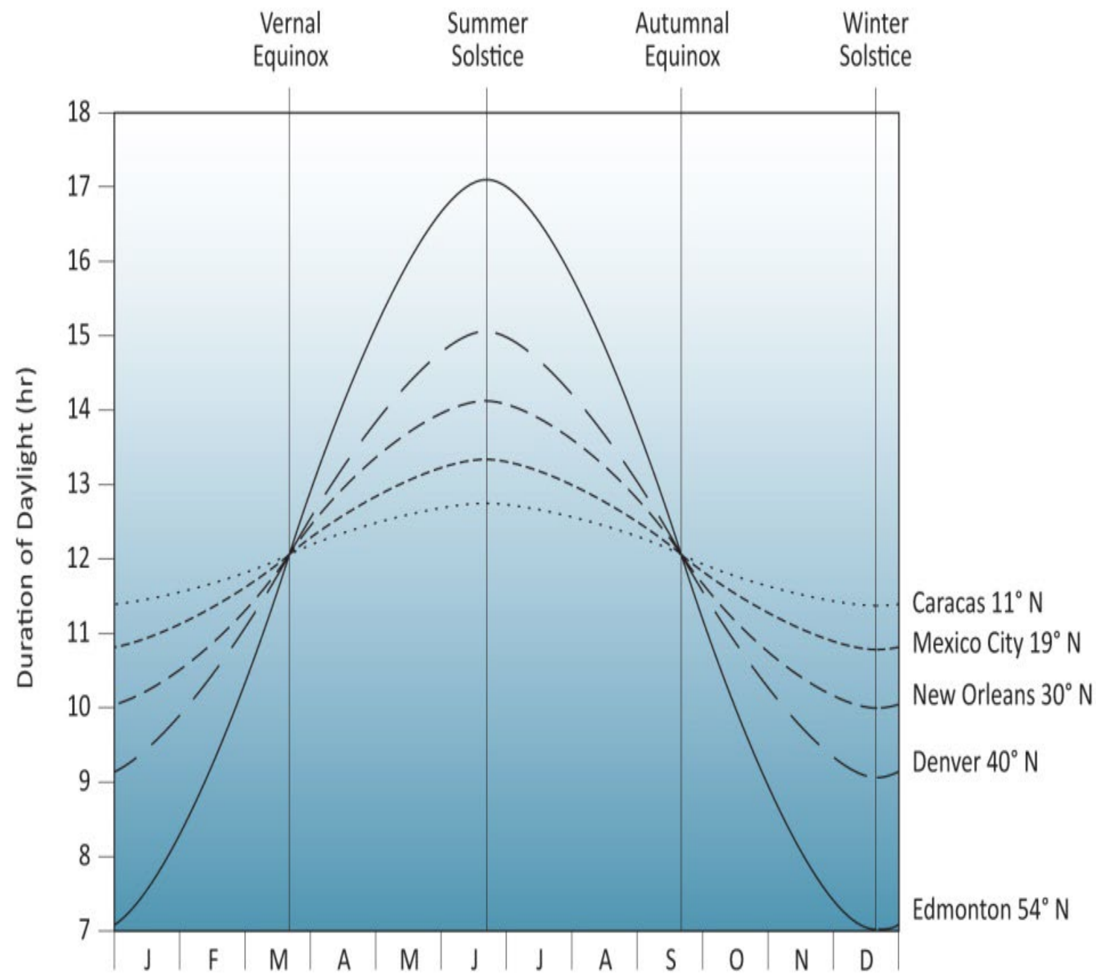
- The Northern Hemisphere summer solstice (left)
- The Northern Hemisphere winter solstice (right)

Earth's Revolution and Seasons

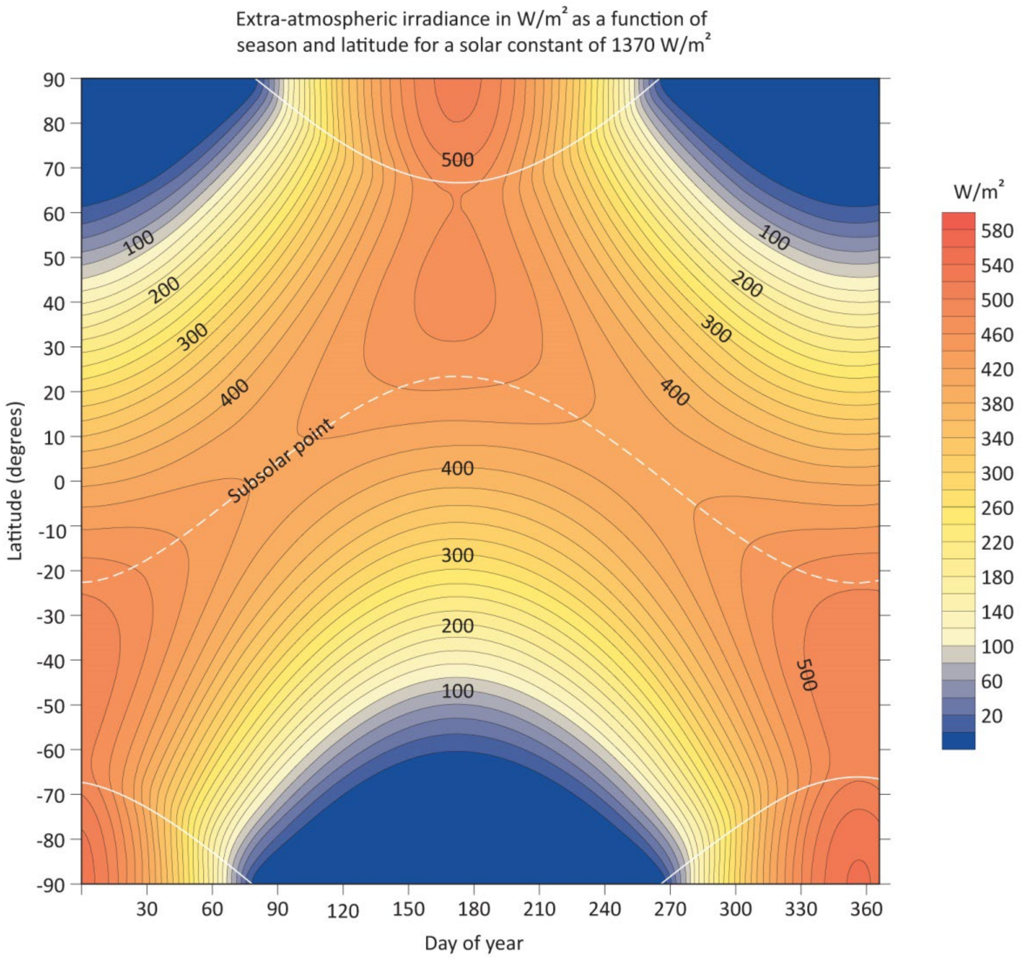
- At the autumnal and spring equinoxes, the noon solar altitude is greatest (90 degrees) at the equator



- With increasing latitude (toward the Poles), the seasonal contrast in length of daylight also increases
- Day length at the equator doesn't change through the course of the year
  - Always around 12 hours
- At 60° N, daylight varies
  - 5 hrs 53 min on 22 December
  - 18 hrs 52 min on 21 June.

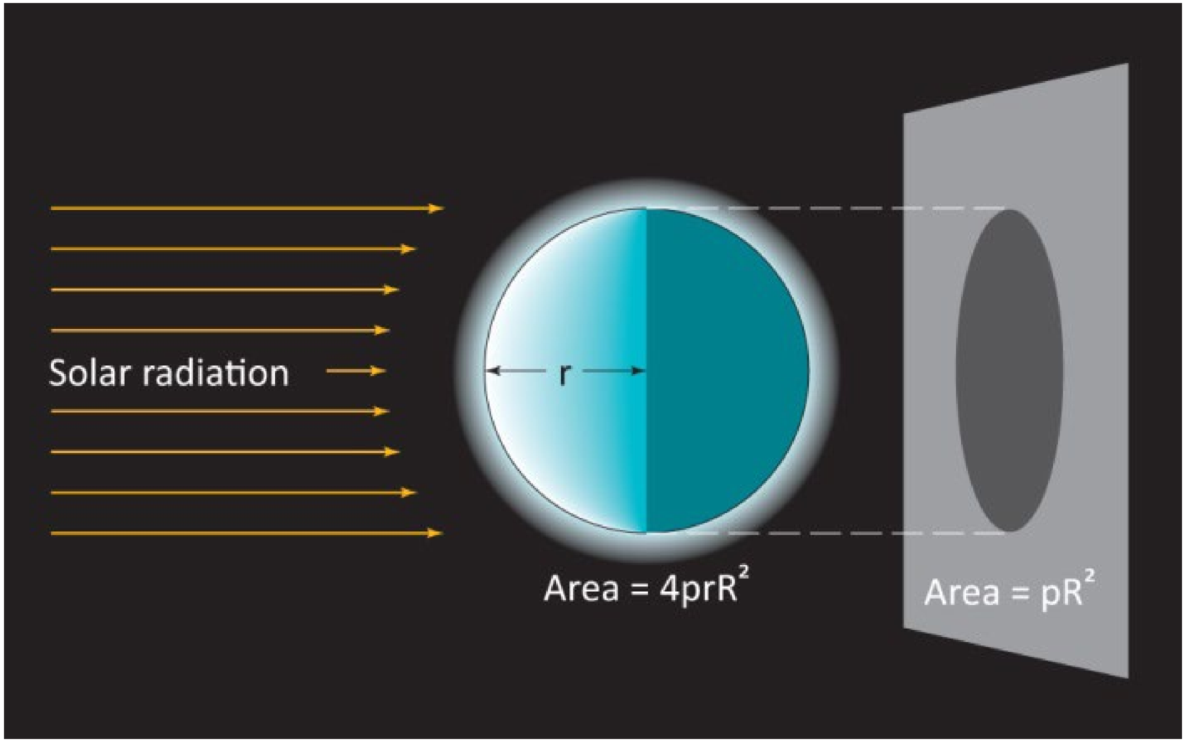


The Solar Constant



- **Solar constant -** rate that solar radiation strikes a flat surface on the outer edge of the atmosphere, perpendicular to the radiation when Earth is at its mean distance from the Sun
  - Averages 1368 W/m^2
- More solar radiation is received in the tropical than polar regions

The Solar Constant



- Earth intercepting a continuous stream of disks of solar energy
- Total energy received at the top of Earth's atmosphere is ¼ the solar constant
  - 342 W/m2

Transfer of Energy
Electromagnetic Radiation

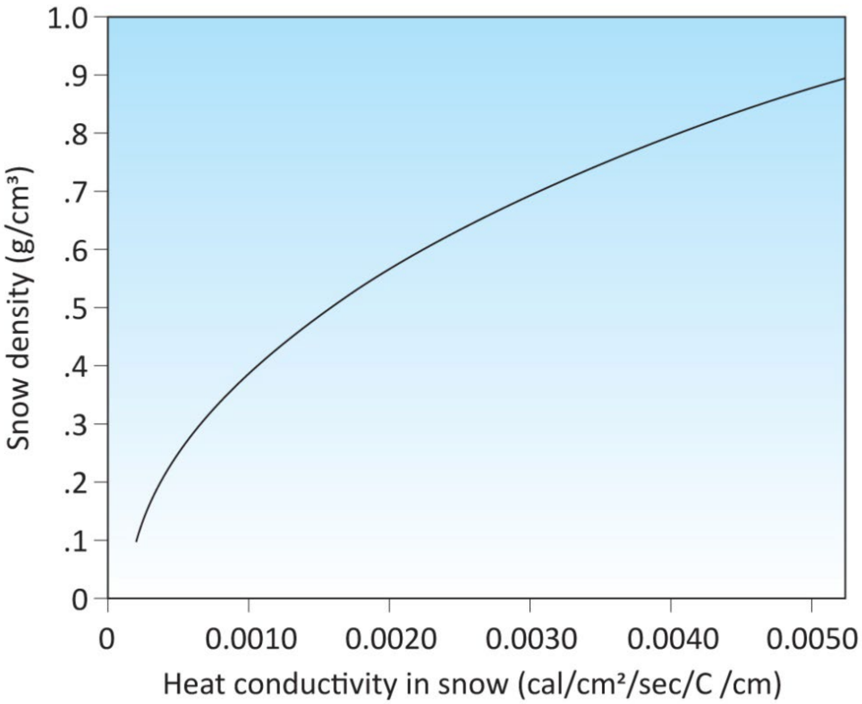
- Electromagnetic radiation transfers energy at the speed of light through the vacuum of space
  - Principal means of the climate system gaining energy from the Sun
  - Principal means energy escapes the planet to space
- **Radiational heating -** an imbalance in the flux of radiation when an object absorbs radiation faster than it emits radiation and its temperature rises
- **Radiational cooling -** an imbalance in the flux of radiation when an object emits radiation faster than it absorbs radiation and its temperature decreases

Transfer of Energy
Conduction & Convection

- **Conduction -** transfer of kinetic energy of atoms or molecules through collisions between neighbors, or simply the transfer by contact (substance-to-substance)
- **Thermal conductivity -** ability of a substance to conduct heat
- **Heat conductivity -** ratio of the rate of heat transport across an area to the temperature gradient

Substance	Heat Conductivity
Copper	0.92
Aluminum	0.50
Iron	0.16
Ice (at O °C)	0.0054
Limestone	0.0048
Concrete	0.0022
Water (at 10 °C)	0.0014
Dry sand	0.0013
Air (at 20 °C)	0.000061
Air (at 0 °C)	0.000058

Conduction & Convection



- A substance with high heat conductivity will conduct heat through itself
  - metals
- A substance with low heat conductivity is a good insulator
  - air, snow

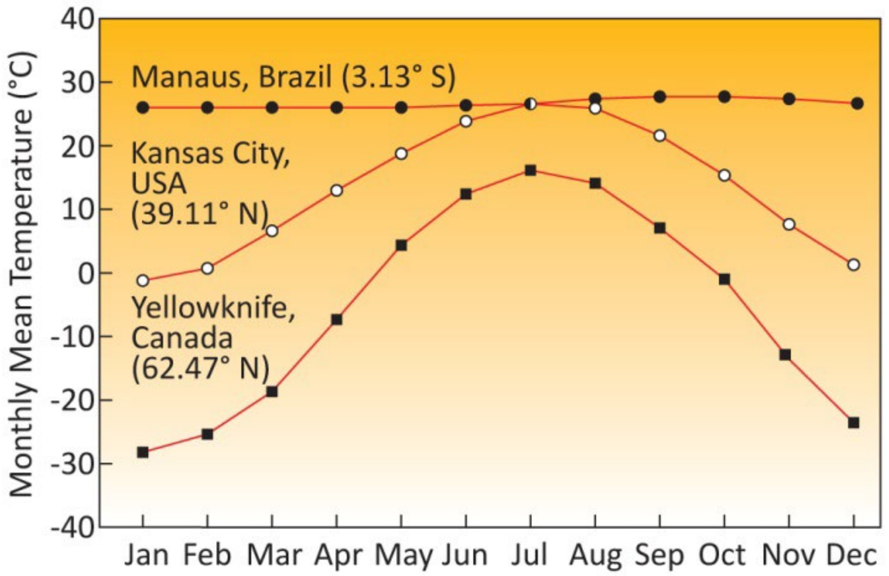
- **Convection -** transporting heat by fluid motions within the fluid itself
- **Buoyancy -** an upward-directed force is exerted upon a parcel of air by virtue of the density difference between the parcel and the surrounding air
  - Cooler, denser, heavier air sinks downward, replacing lighter air that rises
  - Ascending warm air expands, cooling until it becomes denser than surrounding air and sinks back to the ground
  - Cooler air, now in contact with the ground, is warmed and rises, having been displaced by cooler, denser air

Controls on Climate Characteristics

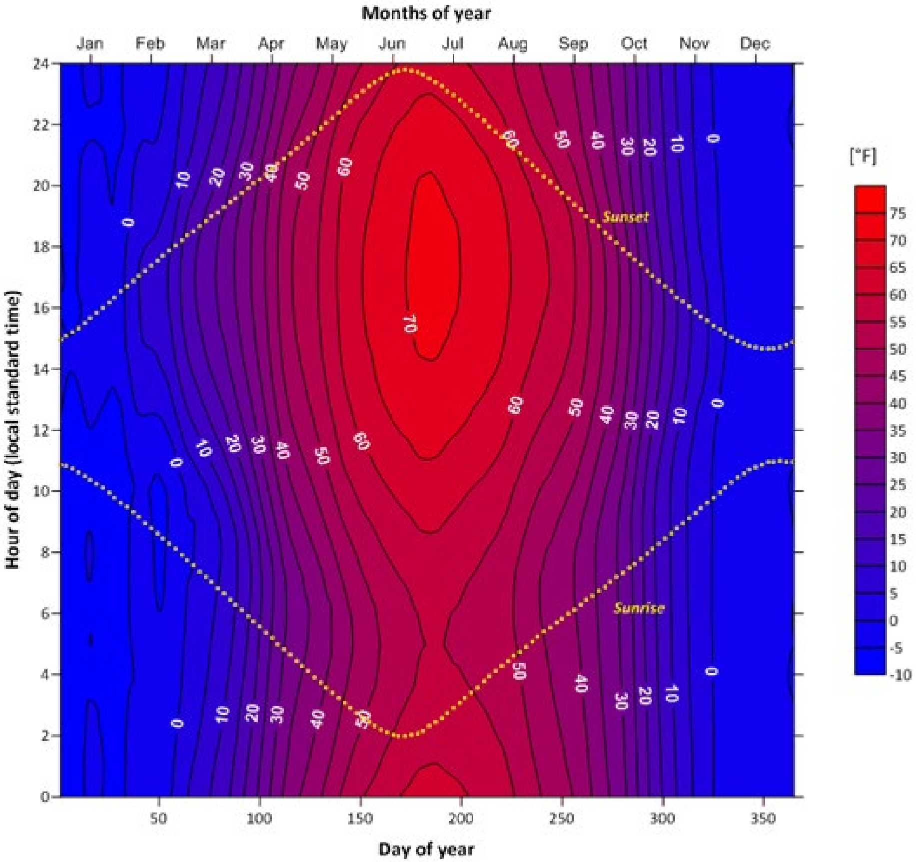
- Air temperature fluctuates hourly, daily, seasonal and by location
- Climate characteristics identified by patterns of variations
- Earth's radiation budget and movements of air masses regulate air temperature locally
  - Radiation budget is primarily influenced by latitude, season and hour of the day
  - Latitude defines the path of the Sun through the local sky, intensity and duration of solar radiation (day length and sun angle)

Latitudinal Influences

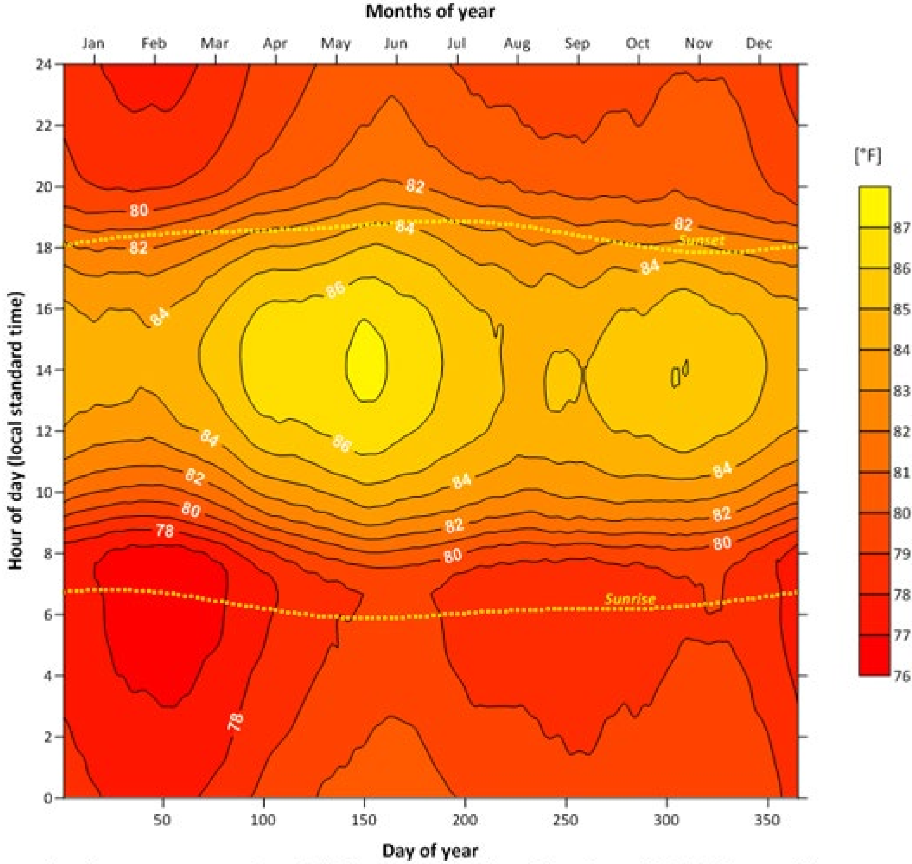
- Between the Tropic of Cancer at 23° 27’ N and the Tropic of Capricorn at 23° 27’ S, there is modest solar radiation variation
- Differences between day and night temperatures are greater than between seasons
- Traveling away from the tropics, the seasonal variation increases to such a degree that, poleward of the Arctic and Antarctic circles, they receive little or no solar radiation in winter seasons, but near constant sunlight in spring and summer



Latitudinal Influences



Hourly temperatures at Fairbanks, AK as a function of day of year (1981-2010 normals)



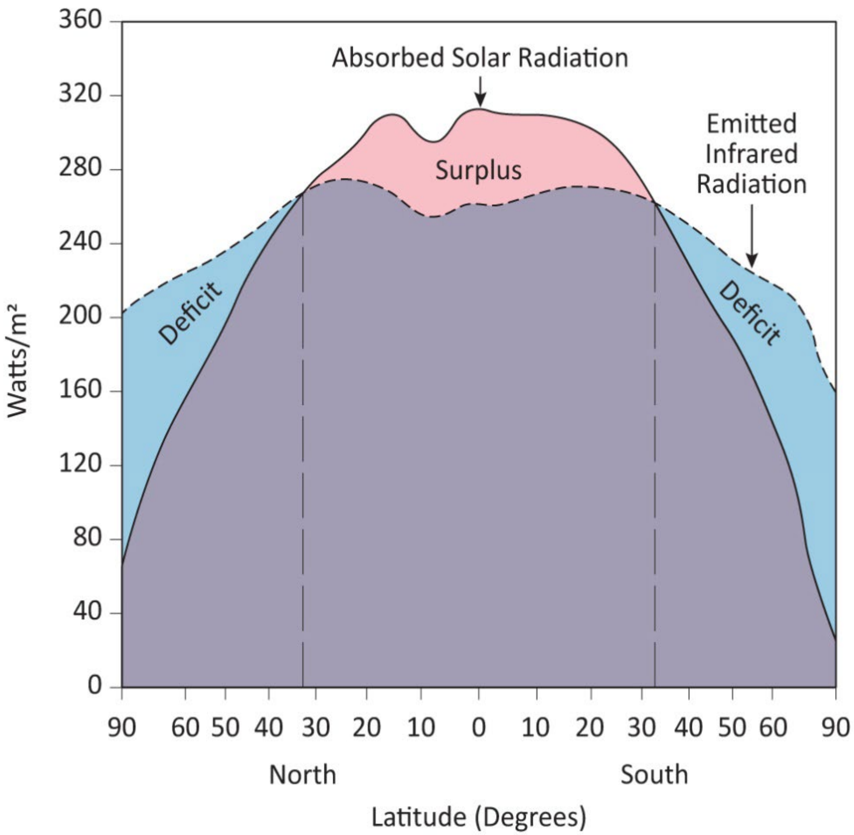
Hourly temperatures at Guam Intl Airport, as a function of day of year (1981-2010 normals)

- Tropical vs Polar hourly temperatures

Latitudinal Influences

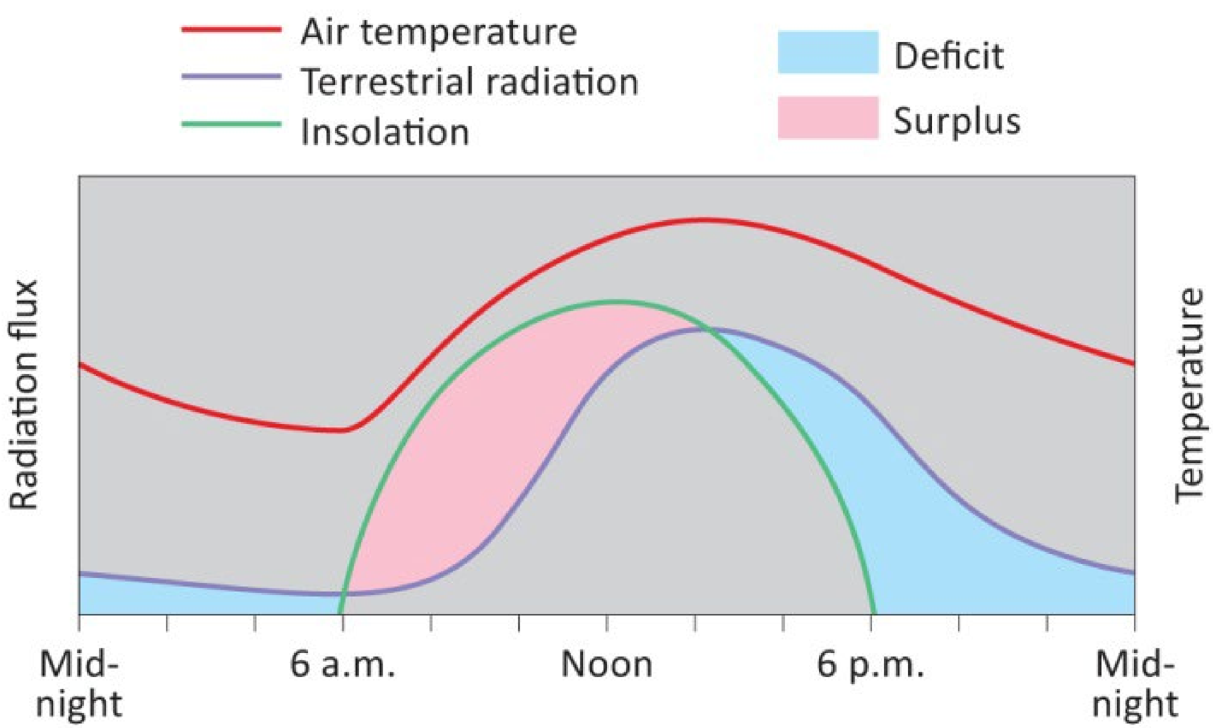
- *Meteorological seasons* - successive 3-month intervals centered on the typical occurrence of the warmest and coldest months of the year
    - Spring: March, April and May
    - Summer: June, July and August
    - Autumn: September, October and November
    - Winter: December, January and February
  - More uniform than astronomical seasons

Latitudinal Influences



- Lower temperatures at higher latitudes means the surface emits less IR radiation
  - In higher latitudes, more annual IR radiational cooling occurs than solar radiation heating
  - In the tropics more annual solar radiation heating occurs than IR radiational cooling
- Over the entire globe, the absorbed solar radiation must equal the emitted IR radiation to space,
  - Without balance, global climate change occurs

Latitudinal Influences



- **Diurnal -** lag between solar radiation and air temperature

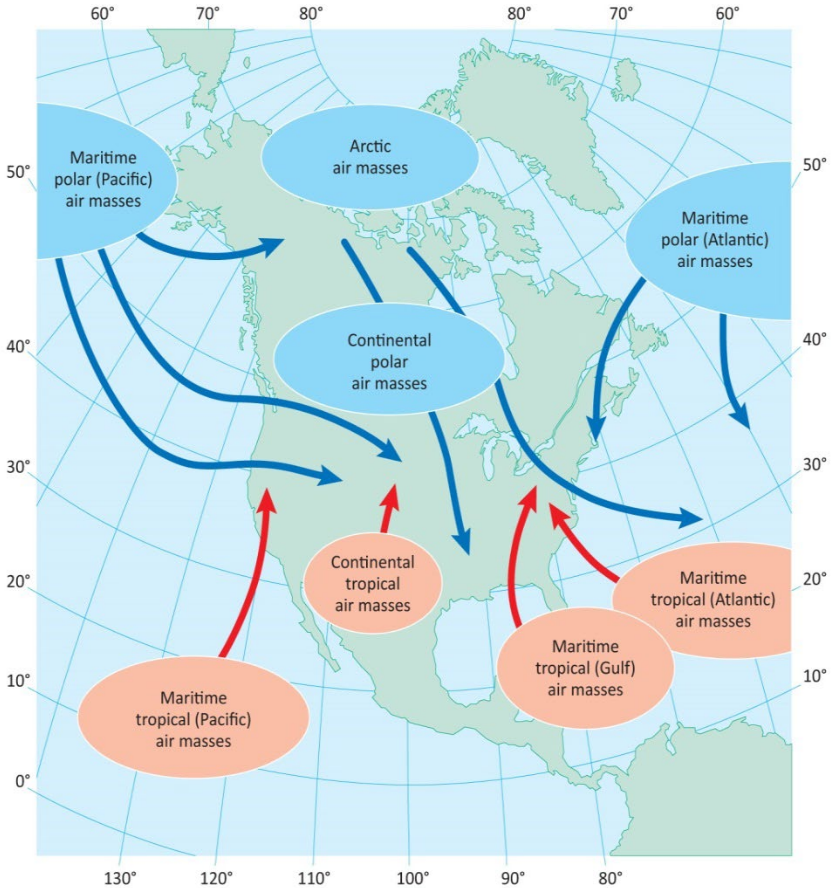
Clouds

- Clouds are an element in the atmosphere that alter the amount of radiation reaching the surface, making them a substantial control on temperatures
  - Composed of water droplets and/or ice crystals
  - Can reflect sunlight or scatter the light energy, which diffuses the effect of radiant energy exchange and results in cooling at Earth's surface
  - Can assist in the greenhouse effect by absorbing IR radiation, so a cloudy night is typically warmer than a clear night
- A cloud's capacity to heat or cool depends, most importantly, on the height of the cloud followed by its size then the constituents of the cloud itself
- Overall, clouds cool the global climate system
  - The more extensive the cloud cover, the cooler the planet
  - The less cloud cover, the warmer the planet

Surface Characteristics

- Solar radiation warms a dry surface more than a moist surface or vegetation
  - Moisture in the surface must first be evaporated
- Dark surfaces, with lower albedo, will warm quicker than a light one, with higher albedo
- **Microclimate** - the result of surface features influencing the climate character within a few square feet to multiple square kilometers

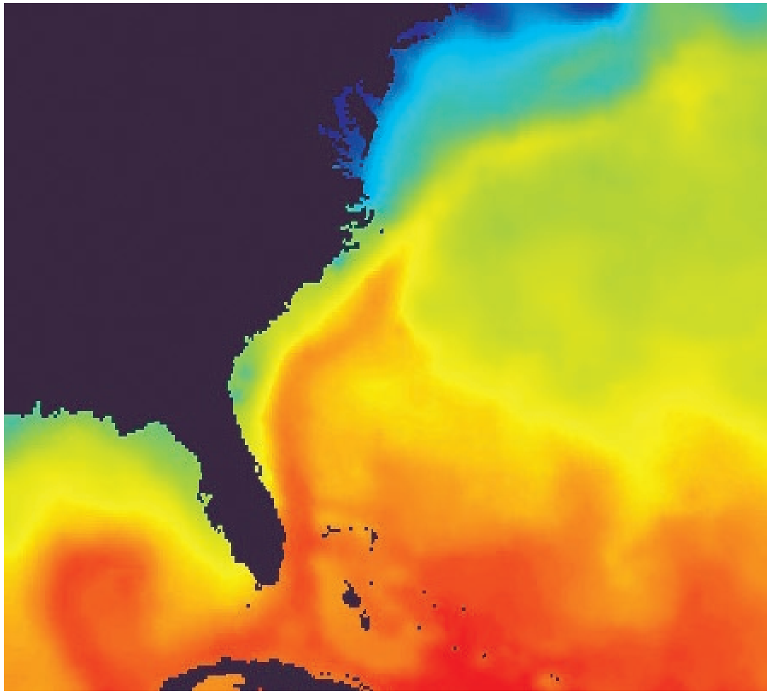
Air Mass Exchanges



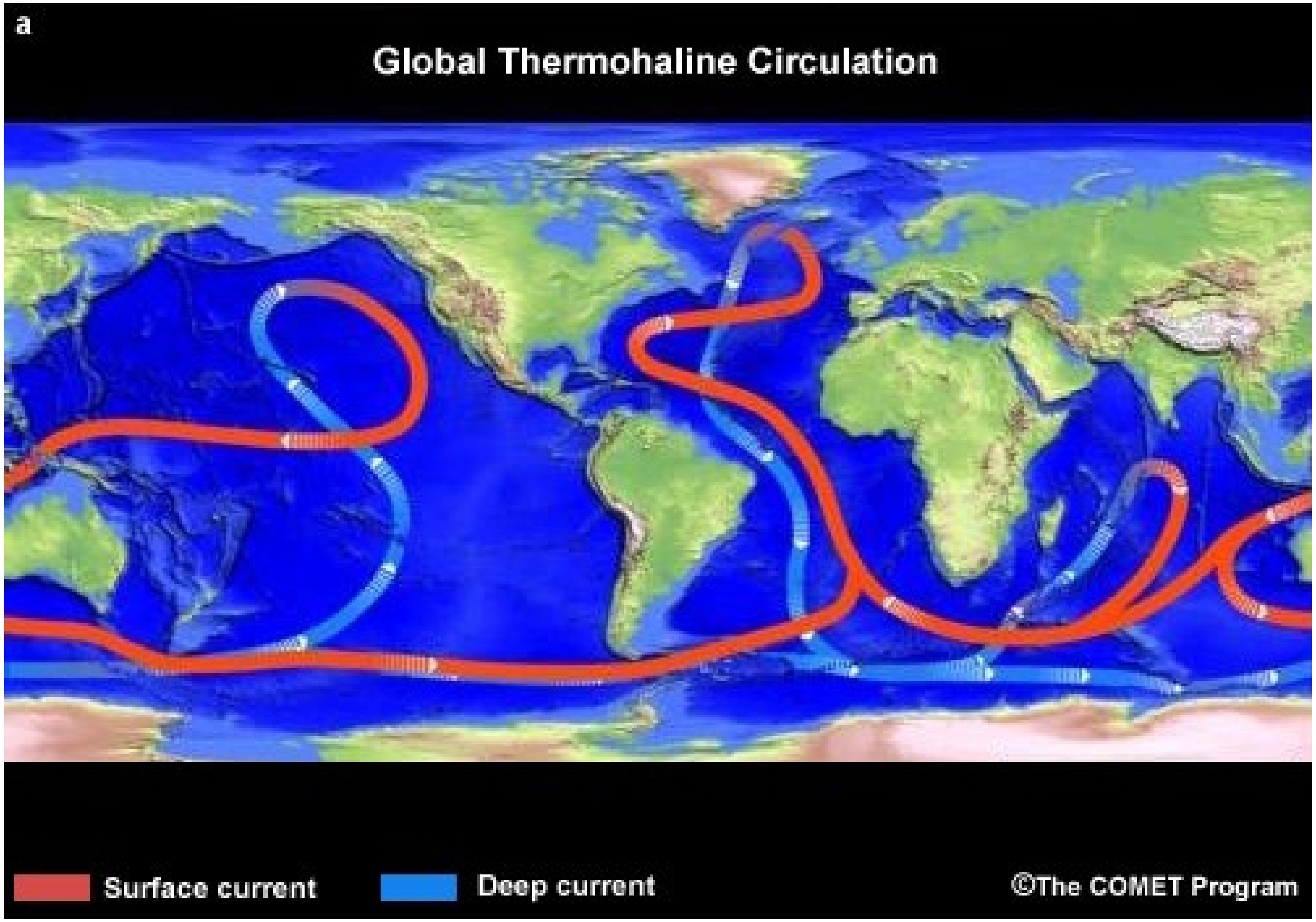
- **Air mass -** huge volumes of air, covering thousands of square kilometers, which are relatively uniform horizontally in temperature and humidity
- *Source region*, the surface over which it forms and travels determines the characteristics of an air mass
  - Air mass that forms at high latitudes over a cold, snow or ice covered surface is chilled by the source below
  - Air mass forming over a warm surface at low latitudes is warmed from below
  - Air masses that develop over the ocean are humid
  - Air masses developing over land are dry

Ocean Circulation

- Ocean & Atmosphere
  - Surface water warmer than the overlying air is a *heat source* for the atmosphere, transferring it from sea to air by conduction and convection
  - Surface water cooler than the overlying air is a *heat sink* for the atmosphere, conducting it from air to sea
  - Heat absorbed during evaporation and IR emissions moves energy from sea to air
- Latitudinal
  - Warm surface currents (Gulf Stream) flow from the tropics into middle latitudes, supplying heat to the cooler middle latitude troposphere
  - Cold surface currents (California Current) flow from high to low latitudes, absorbing heat from relatively warm troposphere and greater solar radiation in the tropics



Global Thermohaline Circulation



- **Thermohaline circulation -** the density-driven movement of water masses brought about by variations in temperature and salinity
- **Meridional overturning circulation (MOC) -** global-scale heat transporting circulation

Big Ideas

- Temperature is an important and widely used climatic parameter
  - An indicator of energy flow within the climate system
- Heat energy is transferred from warmer locales to colder locales in response to a temperature gradient via:
  - Radiation
  - Conduction
  - Convection
  - Phase changes of water
- Specific heat of a substance is a measure of temperature change of that substance associated with an input or output of heat energy
  - An unusually high specific heat is one of the reasons why water plays an important role in Earth's climate system
- Large bodies of water have a greater capacity for storing heat energy, helping to dampen changes in temperature (high thermal inertia)
  - Explains the difference between maritime and continental climates

Big Ideas

- Operating at the global scale, differences in rates of radiational heating and radiational cooling produce temperature gradients between Earth's surface and atmosphere, as well as between the tropics and higher latitudes
  - Heat is transported from Earth's surface to atmosphere via phase changes of water (latent heating) and conduction and convection (sensible heating)
  - Heat is transported from the tropics to higher latitudes via air mass exchange, storms, and ocean circulation
- The combination of the local radiation budget plus air mass advection controls the annual and diurnal variations in air temperature near Earth's surface
  - Climatic boundary conditions examples: incoming solar radiation, proximity to large bodies of water, Earth's surface characteristics, cloud cover

Key Terms

- Energy
- Entropy
- Second law of thermodynamics
- Wavelength
- Frequency
- Visible radiation
- Infrared (IR) radiation
- Blackbody
- Wien's displacement law
- Stefan-Boltzmann law
- Global radiative equilibrium
- Greenhouse effect
- Global warming
- Industrial Revolution
- Chlorofluorocarbons
- Global warming potential
- Scatter
- Reflection
- Albedo
- Earth's planetary albedo
- Absorbtion
- Stratospheric ozone gradient
- Temperature gradient
- Temperature
- Heat
- Meridional Overturning Circulation

- Law of conservation of energy
- Absolute zero
- Joule
- Thermometer
- Circle of illumination
- Aphelion
- Perihelion
- Solar Altitude
- Solar Declination
- Tropic of Cancer & Capricorn
- Solstice
- Arctic & Antarctic Circle
- Equinox
- Solar Constant
- Radiational heating & cooling
- Conduction
- Thermal conductivity
- Heat conductivity
- Convection
- Buoyancy
- Diurnal
- Microclimate
- Air Mass
- Thermohaline Circulation