Course Outline

Climate 101

- 2/7 Introduction: The Earth System
- 2/14 Energy, Radiation, & Temperature
- 2/21 Winds, Currents, and Water
- 2/28 Climates of the Past
- 3/7 Modern Climate Change

Class Web Site

http://climate101.atmos.colostate.edu

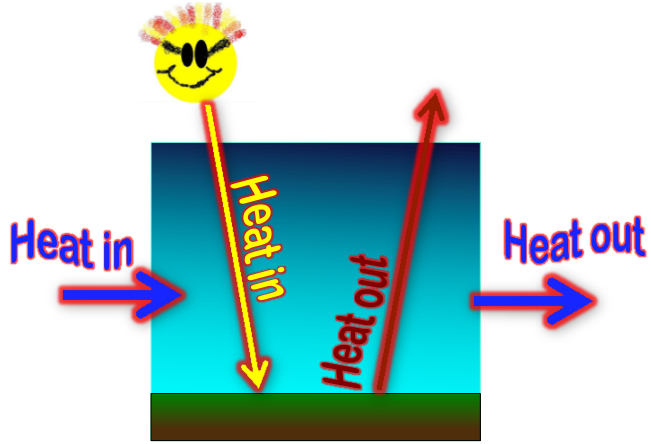
- All slides as printable handouts
- Supplemental readings
- Videos
- Links to more resources

Weather vs Climate

what's the difference?

- If you don't like the weather:
  - *Wait five minutes!*
- If you don't like the climate:
  - *Move!*

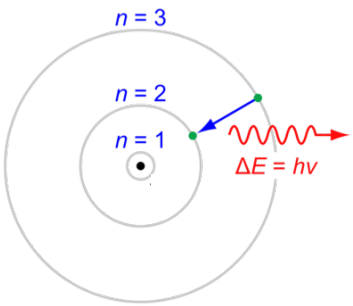
Heat Budgets



Radiation and the Planetary Energy Balance

- Electromagnetic Radiation
- Solar radiation warms the planet
- Conversion of solar energy at the surface
- Absorption and emission by the atmosphere
- The greenhouse effect
- Planetary energy balance

Waves and Photons



Long Waves = small photons

Short Waves = BIG PHOTONS

Is light a wave? YES!

Is light a particle? YES!

All light travels at the same speed

Think of short waves as BIG HEAVY particles

Think of longer waves as small, lightweight particles

Defining Energy is Hard!

- "Energy is the capacity to perform work"
  - (but physicists have a special definition for "work," too!)
- Part of the trouble is that scientists have "appropriated" common English words and given them special meanings
- But part of the trouble is that the concept is absolutely central to understanding the physical world, so deeply buried in our language it's hard to get our heads around

Conservation of Energy

- Energy can be stored
- Energy can move from one piece of matter to another piece of matter
- Energy can be transformed from one type of energy to another type of energy
- The First Law of Thermodynamics:
  - During all this moving and transforming the total amount of energy never changes.

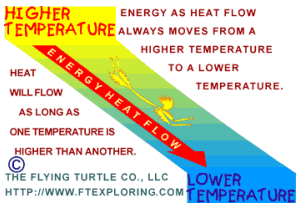
Kinds of Energy

- Radiant Energy -- light
- Kinetic Energy -- motion
- Gravitational Potential Energy -- height
- "Internal Energy"
  - Temperature, Pressure -- hot air
  - Chemical energy
  - Nuclear energy
- Transfers and conversions among different kinds of energy power everything that happens in our climate!

If Energy is Conserved …

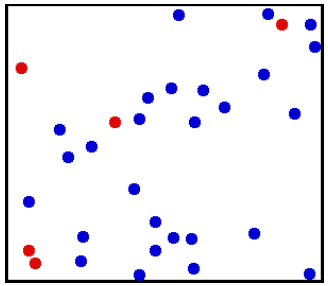
then why do we need to "conserve energy?"

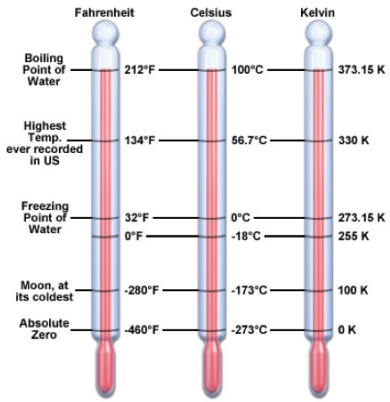
- Total energy is conserved (First Law), but not its usefulness!
- Second Law of Thermodynamics: Energy flows "downhill" from highly concentrated (hot) forms to very dilute (cold) forms



- Gasoline burned in your car (hot) makes it move
- Turbulence and friction of tires on road dissipated as heat
- Heat radiated to space (cold)

Temperature is Motion



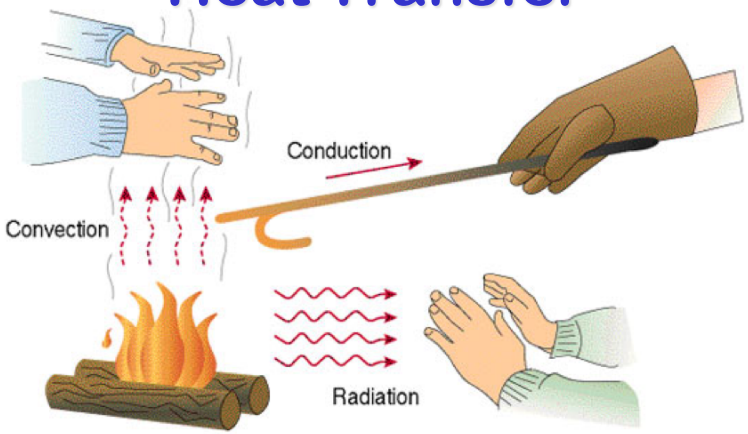


Temperature is a measure of the average kinetic (motion) energy of molecules

- K.E. = ½ mv^2
  m = mass, v = velocity
- So…temperature is a measure of air molecule speed (squared)

Thermometers are speedometers!

Heat Transfer



Conduction is by hot molecules colliding with neighbors
Convection is by hot stuff moving in bulk from place to place

Electromagnetic Radiation

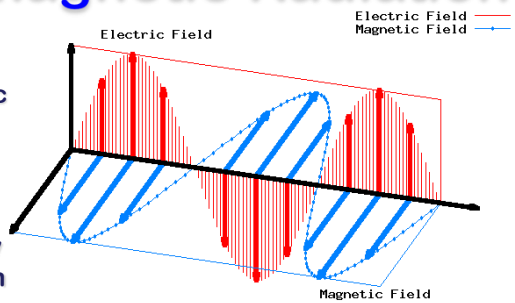
Changing electric fields create changing magnetic fields …

and vice versa!

This makes energy move even through empty space

We can see it, feel it

Plants harvest it directly, and we harvest them!



Travels at 3×10^8 m/s
= 186,000 miles / sec !

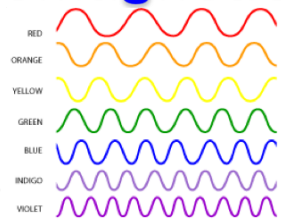
Distance it goes in one cycle is called the wavelength

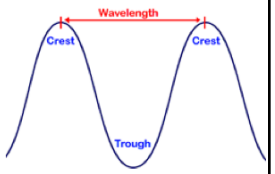
Electromagnetic Radiation

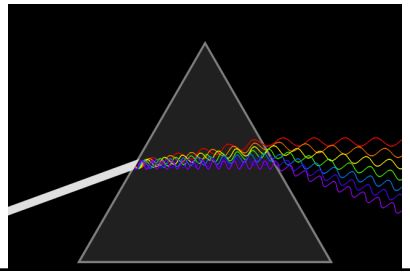
Radiation travels as waves or photons

Waves do not require molecules to propagate

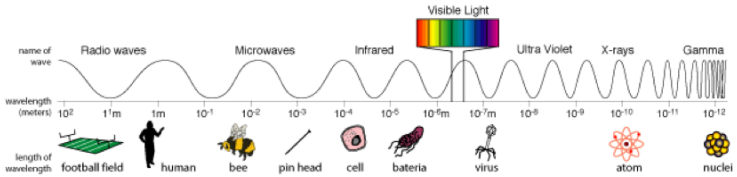
Shorter waves carry more energy than longer ones







Electromagnetic Radiation Spectrum



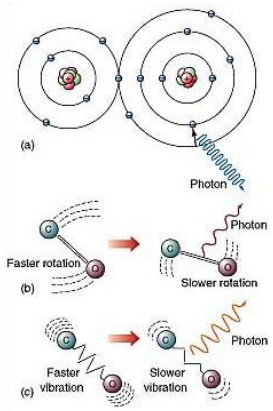
Shorter waves carry more energy than longer waves

Electromagnetic waves interact with matter at similar scales (sizes) as the waves

Thermal Radiation

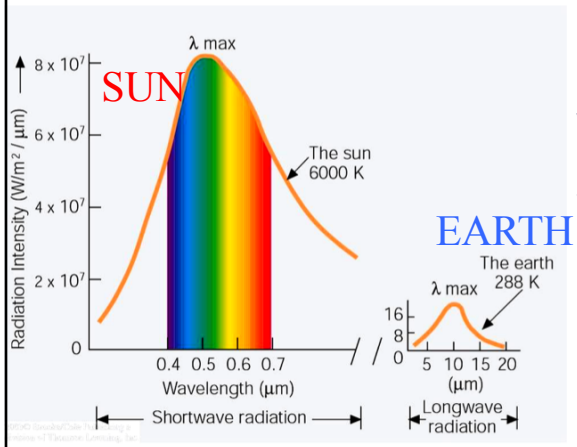
"Everything emits heat"

Atoms, Molecules, and Photons



- Atmospheric gases are made of molecules
- Molecules are groups of atoms that share electrons (bonds)
- Photons can interact with bonds
- Transitions between one state and another involve specific amounts of energy

Thermal Emission



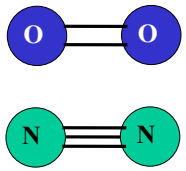
Both are almost perfect blackbodies!

The hot sun radiates at shorter (visible) wavelengths that carry more energy

Energy absorbed by the cooler earth is then re-radiated at longer (thermal infrared) wavelengths

Dancing Molecules & Heat Rays!

- Nearly all of the air is made of oxygen (O_2) and nitrogen (N_2) in which two atoms of the same element share electrons

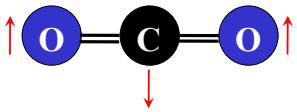


- Infrared (heat) energy radiated up from the surface can be absorbed by these molecules, but not very well

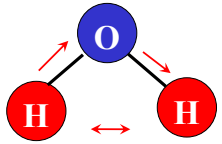
Diatomic molecules can vibrate back and forth like balls on a spring, but the ends are identical

Dancing Molecules & Heat Rays!

- Carbon dioxide (CO_2) and water vapor (H_2O) are different!



- They have many more ways to vibrate and rotate, so they are very good at absorbing and emitting infrared (heat) radiation



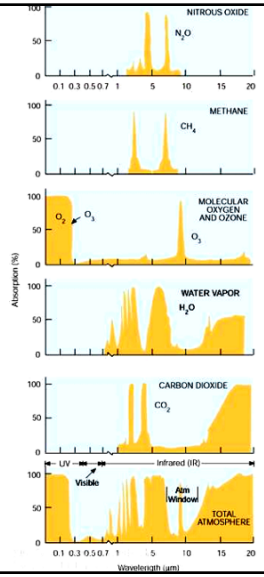
Molecules that have many ways to wiggle are called "Greenhouse" molecules

Atmospheric Absorption

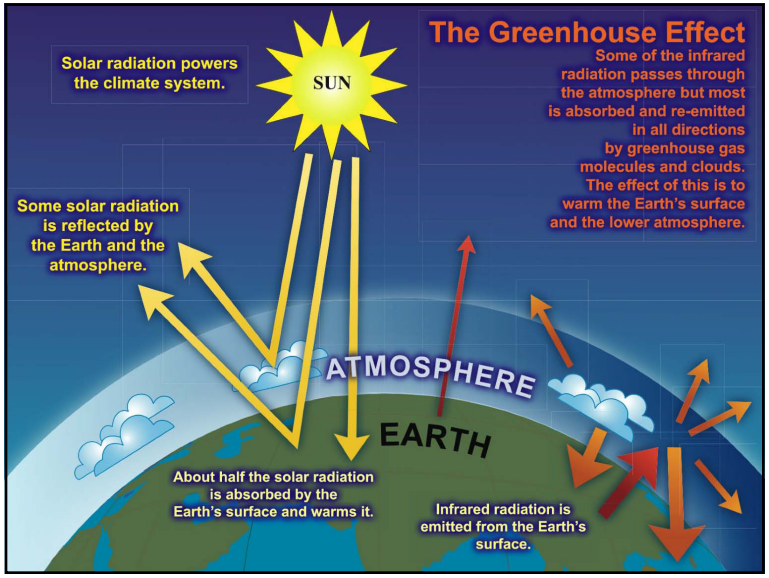
Solar radiation passes rather freely through Earth's atmosphere

Earth's re-emitted longwave energy either fits through a narrow "window" or is absorbed by greenhouse gases and re-radiated toward earth

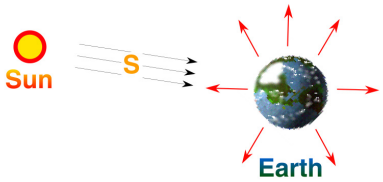
Major LW absorbers:
- Water vapor
- CO_2
- O_3
- Clouds



The Greenhouse Effect



Planetary Energy Balance



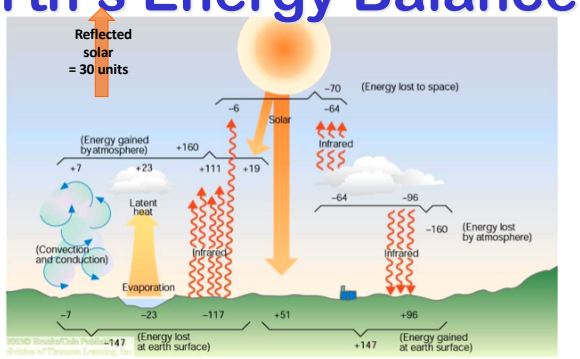
Energy In = Energy Out

$$S(1-\alpha)\pi R^2 = 4\pi R^2 \sigma T^4$$

$$T \approx -18^\circ \mathrm{C}$$

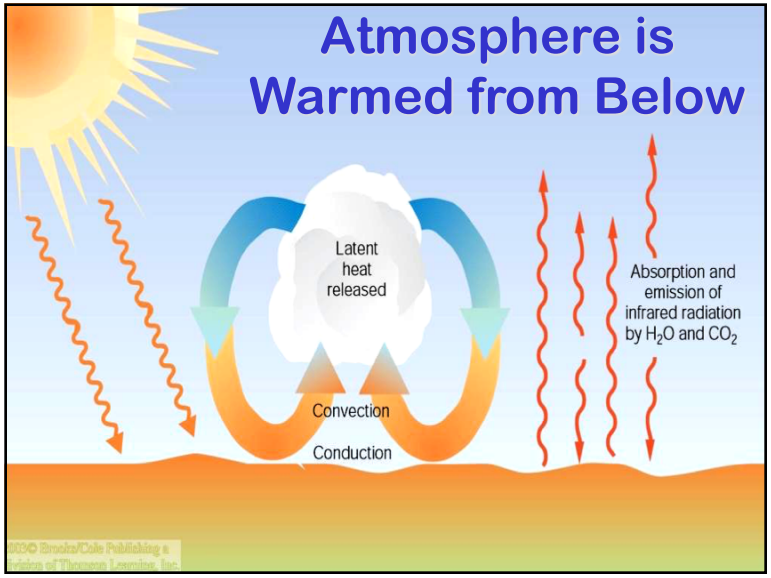
But the observed T_s is about 15° C

Earth's Energy Balance(s)



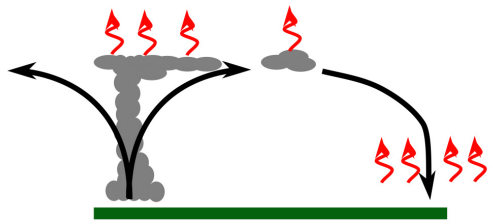
- Surface absorbs 51 units of sunshine, plus 96 units of thermal IR! (total = 147 units, 47% more than incoming solar!)
- Surface emits only 117 units, gives the rest back by evaporating water (23 units) and convection (7 units)

Atmosphere is Warmed from Below



The Job of the Atmosphere

is to let the energy out!

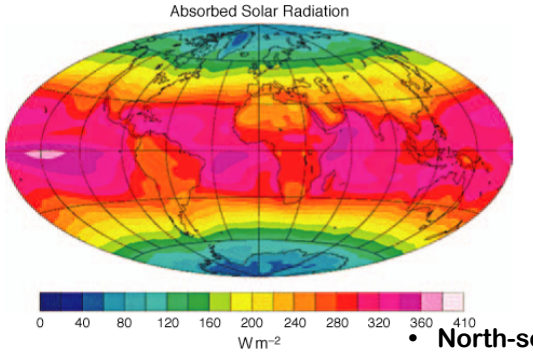


Hot
"Piles up" in tropics

Cold
"Escapes" near poles and aloft

The movement of the air (and oceans) allows energy to be transported to its "escape zones!"

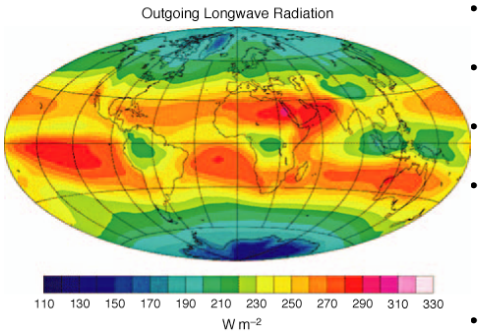
Energy In



Annual Mean

- North-south contrast
- Land-sea contrast
- Ice and snow
- Deserts vs forests

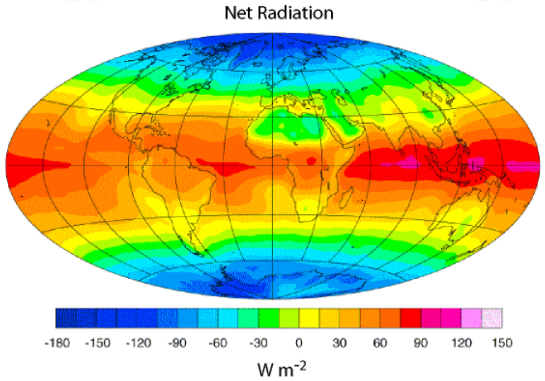
Energy Out



Annual Mean

- Given by $\varepsilon\sigma T^4$ (which T?)
- Combined surface and atmosphere effects
- Decreases with latitude
- Maxima over subtropical highs (clear air neither absorbs or emits much)
- Minima over tropical continents (cold high clouds)
- Very strong maxima over deserts (hot surface

Energy In minus Energy Out

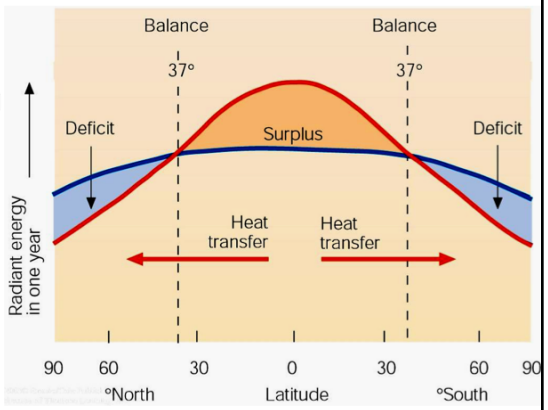


- Incoming solar minus outgoing longwave
- Must be balanced by horizontal transport of energy by atmosphere and oceans!

Earth's Energy Balance

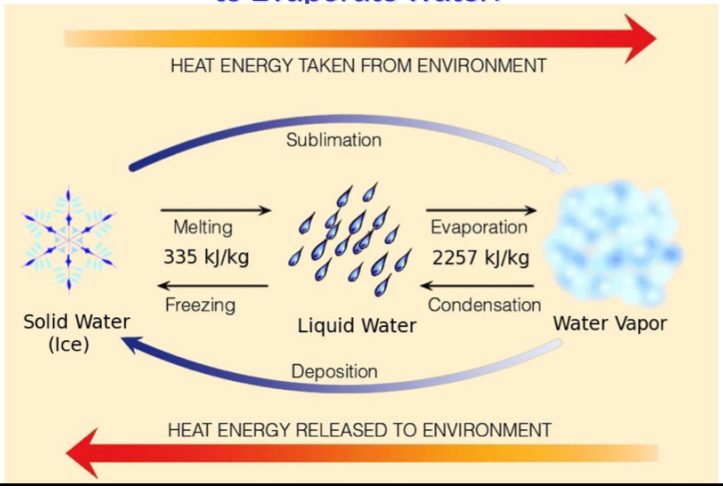
Earth's annual energy balance between solar insolation and terrestrial infrared radiation is global but not local

The global balance is maintained by transferring excess heat from the equatorial region toward the poles

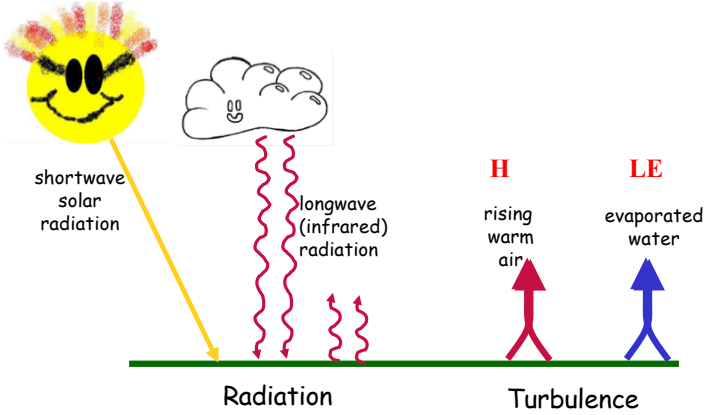


It Takes a Lot of Energy

to Evaporate Water!

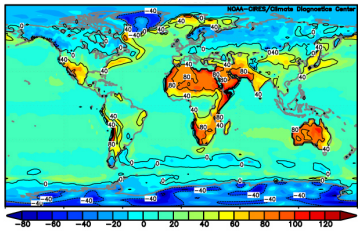


Energy Balance of Earth's Surface

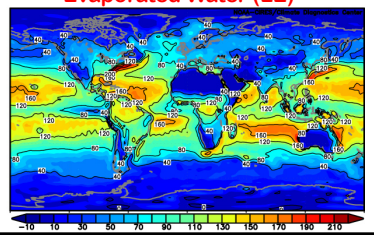


Energy from the Surface to the Air

Rising Warm Air (H)

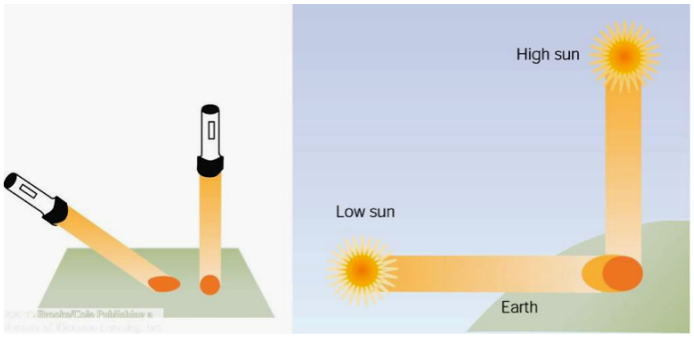


Evaporated Water (LE)



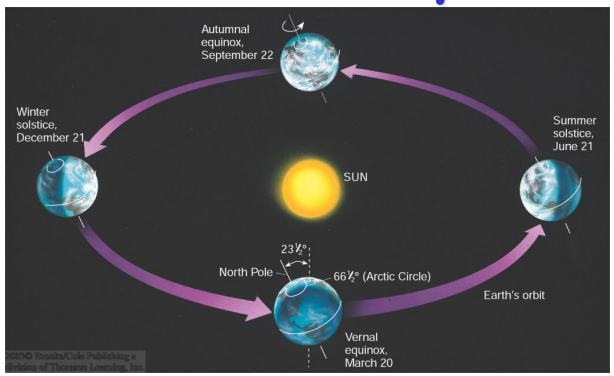
- Energy absorbed at the surface warms the air
- Some of this energy is transferred in rising warm "thermals"
- But more of it is "hidden" in water vapor

Seasons & Solar Intensity



A sunlight beam that strikes at an angle is spread across a greater surface area, and is a less intense heat source than a beam impinging directly.

Solstice & Equinox

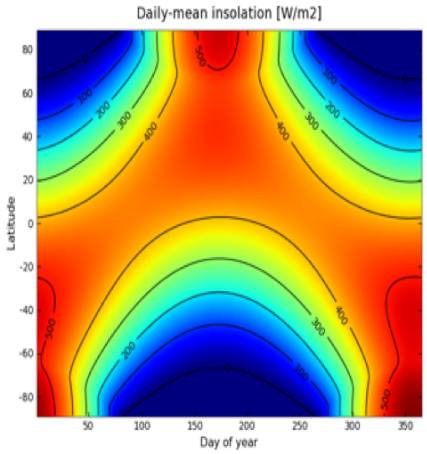


- At solstice, one pole is light & one is dark (24/7)
- At equinox, tilt provides exactly 12 hours of night and 12 hours of day everywhere

Midnight Sun

The region north of the Arctic Circle experiences a period of 24 hour sunlight in summer, where the Earth's surface does not rotate out of solar exposure

Daily Solar at Top of Atmosphere



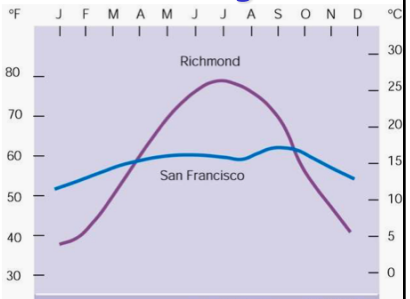
- 75° N in June gets more sun than the Equator!
- Compare N-S changes by seasons
- Very little tropical seasonality

Regional Seasonal Cycles

Regional differences in temperature, from annual or daily, are influenced by geography, such as latitude, altitude, and nearby water or ocean currents, as well as heat generated in urban areas

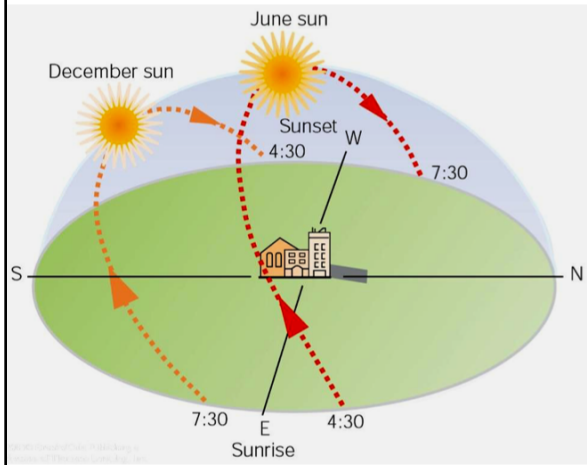
San Francisco is downwind of the Pacific Ocean

Richmond, VA is downwind of North America!



	SAN FRANCISCO		RICHMOND	
	°C	°F	°C	°F
Mean annual temperature	14	57	14	57
Annual temperature range	6	11	22	42
Record high	39	103	41	105
Record low	−3	27	−24	−12

Local Solar Changes



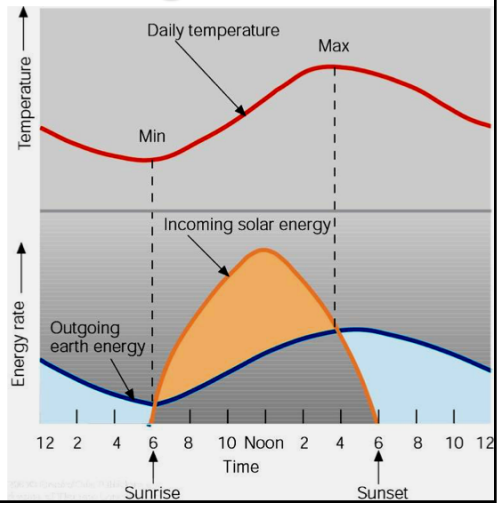
Northern hemisphere sunrises are in the southeast during winter, but in the northeast in summer

Summer noon time sun is also higher above the horizon than the winter sun

Temperature Lags Radiation

Earth's surface temperature is a balance between incoming solar radiation and outgoing terrestrial radiation.

Peak temperature lags after peak insolation because surface continues to warm until infrared radiation exceeds insolation.



Remember

- All energy exchange with Earth is radiation
- Outgoing radiation has longer waves (cooler)
- Longwave radiation is absorbed and re-emitted by molecules in the air (H_2O & CO_2)
- Atmosphere is selectively transparent!Short waves get through, but long waves get trapped
- Recycling of energy between air and surface is the "greenhouse effect"
- Changes of angle of incoming sunlight and length of day & night are responsible for seasons and for north-south differences in climate
- Regional energy surpluses and deficits drive the atmosphere and ocean circulations (wind & currents)