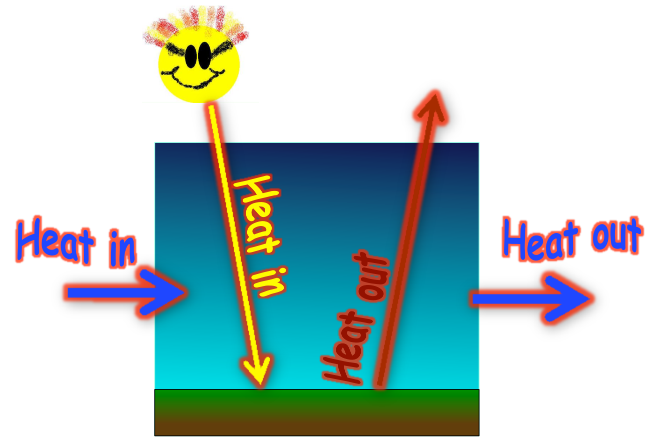
Ever Wonder Why?

- Day is usually warmer than night?
- Summer is usually warmer than winter?
- Miami is usually warmer than Minneapolis?

Heat Budgets



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.**

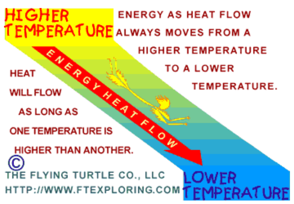
Kinds of Energy

- Radiant Energy -- light
- Kinetic Energy -- motion
- Gravitational Potential Energy -- height
- "Internal Energy"
  - Temperature, Pressure -- hot air
  - Chemical energy
  - Nuclear energy

- Conversions among different kinds of energy power all that happens in the weather and 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

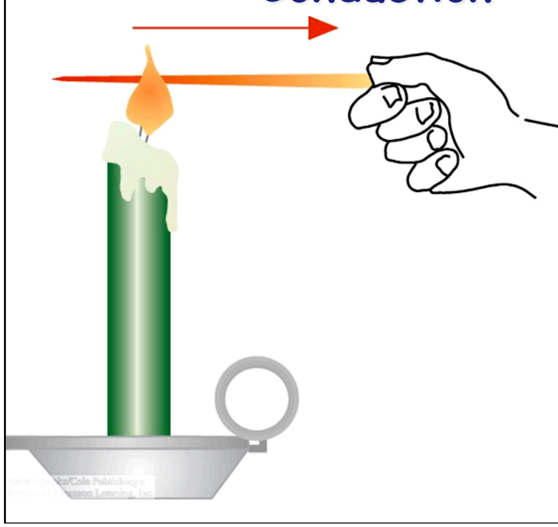


- Gasoline burned in your car (hot) makes it move
- Turbulence and friction of tires on road dissipated as heat
- Heat radiated to space (cold)

Energy Transfer Processes

- *Conduction* - molecules transfer energy by colliding with one another
- *Convection* - fluid moves from one place to another, carrying its heat energy with it.
  - In atmospheric science, convection is usually associated with vertical movement of the fluid (air or water).
  - Advection is the horizontal component of the classical meaning of convection.
- *Radiation* - The transfer of heat by radiation does not require contact between the bodies exchanging heat, nor does it require a fluid between them.

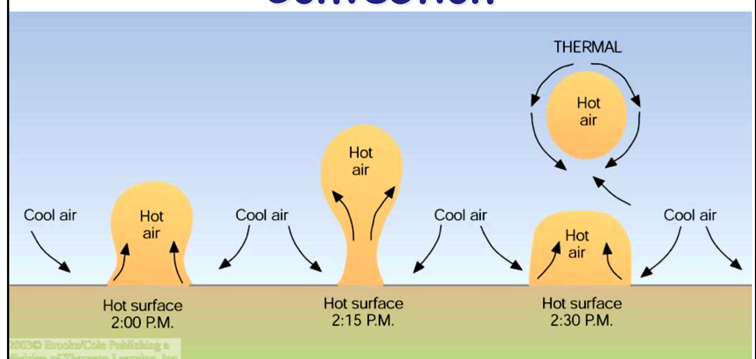
Conduction



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.

Convection



Convection is heat energy moving as warm material from hotter to cooler areas.

Warm air at the ground surface rises as a thermal bubble, expends energy to expand, and hence cools.

Electromagnetic Radiation

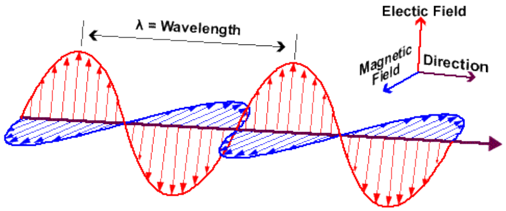
Changing electric fields create changing magnetic fields …

and vice versa!

This makes energy move through space

We can see it, feel it

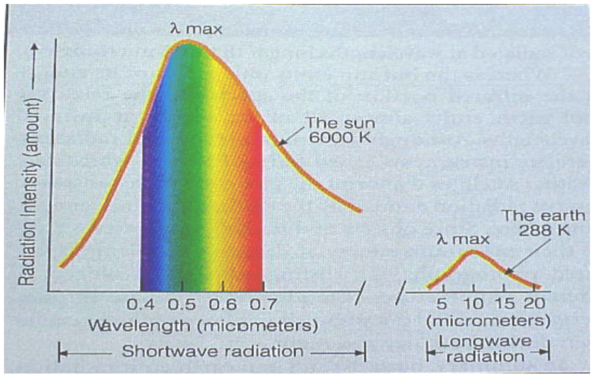
Plants harvest it directly, and we harvest them!



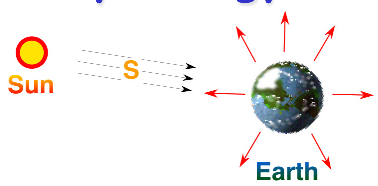
Travels at $3x10^8$ m/s
= 186,000 miles / sec !

Distance it goes in one cycle is called the wavelength

Spectrum of the sun compared with that of the earth



Planetary Energy Balance



Energy In = Energy Out

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

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

But the observed T_s is about 15° C

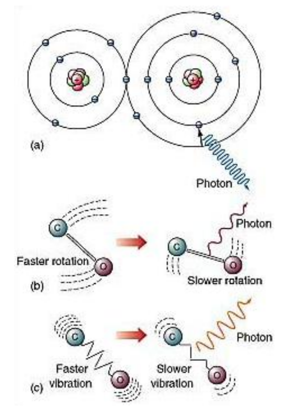
What's Missing
from the 0-D energy balance model?

- Vertical structure
  The "greenhouse effect"
- Energy storage and transport
  The "general circulation" of the atmosphere and oceans

Vertical Structure is Crucial

- The world is a big place, but the atmosphere is very thin, and most of it is close to the ground
  - About 15% of the atmosphere is below our feet
  - At the top of Long's Peak, the figure is 40%
  - You are closer to outer space than you are to Colorado Springs!
- Changes in atmospheric temperature with height are responsible for the "Greenhouse Effect," which keeps us from freezing to death

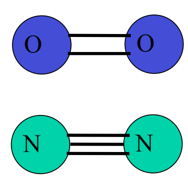
Atoms, Molecules, and Photons



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

Dancing Molecules and Heat Rays!

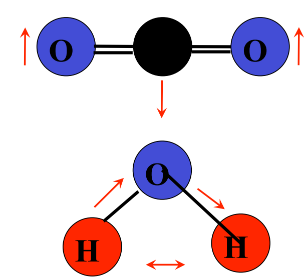
- Nearly all of the air is made of oxygen (O_2) and nitrogen (N_2) in which two atoms of the same element share electrons
- Infrared (heat) energy radiated up from the surface can be absorbed by these molecules, but not very well



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

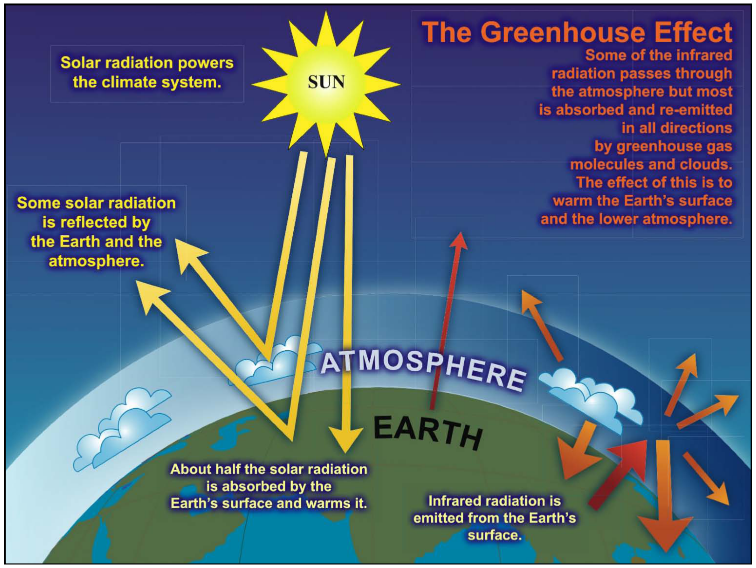
Dancing Molecules and Heat Rays!

- 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

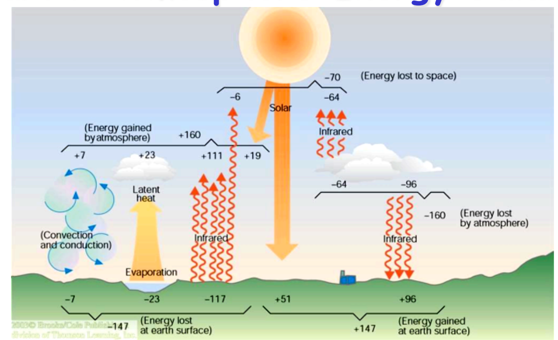


Molecules that have many ways to wiggle are called "Greenhouse" molecules

Absorption spectrum of CO2 was measured by John Tyndall in 1863



Earth-Atmosphere Energy Balance

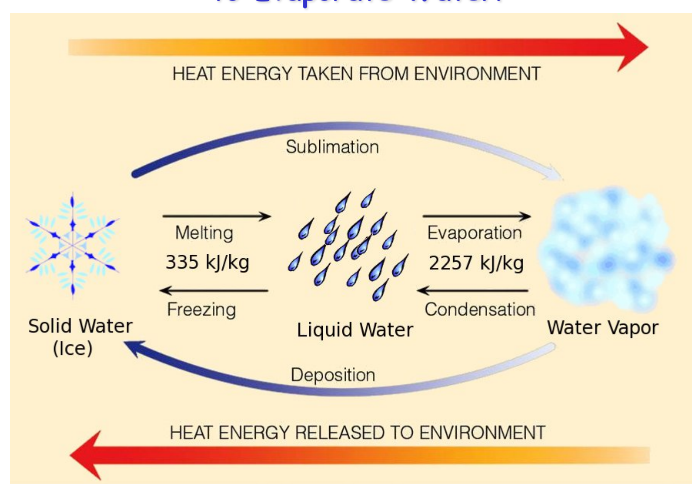


Earth's **surface absorbs the 51 units of shortwave and 96 more of longwave energy units from atmospheric gases and clouds.**

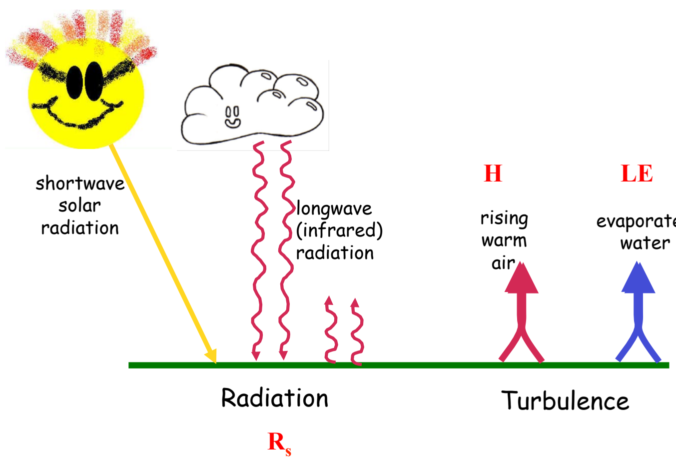
These 147 units gained by earth are due to shortwave and longwave greenhouse gas absorption and emittance.

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

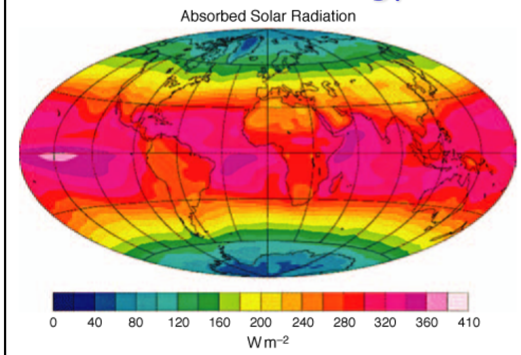
It Takes a Lot of Energy to Evaporate Water!



Energy Balance of Earth's Surface



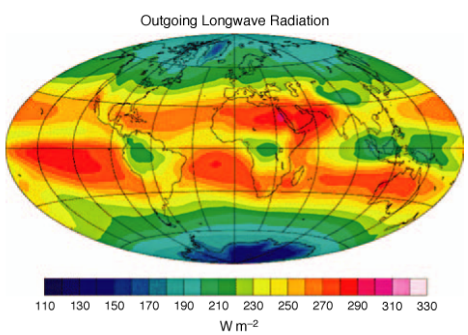
Energy In



Annual Mean

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

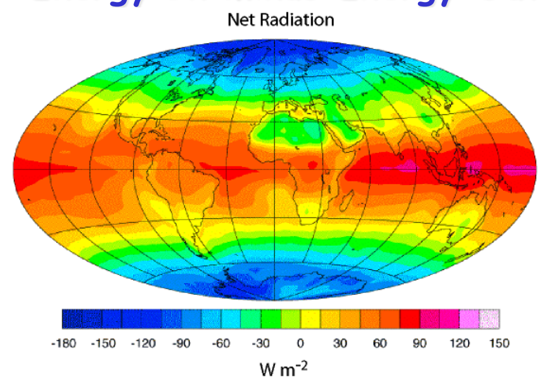
Energy Out



Annual Mean

- Proportional to T^4 (which T?)
- Combined surface and atmosphere effects
- Decreases with latitude
- Maxima over subtropical highs (clear air neither absorbs nor emits much)
- Minima over tropical continents (cold high clouds)
- Very strong maxima over deserts (hot surface, clear atmosphere)

Energy In minus Energy Out

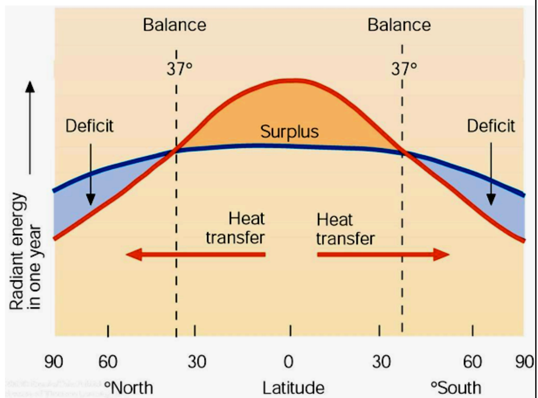


- Incoming solar minus outgoing thermal
- Must be balanced by horizontal transport of energy by atmosphere and oceans!

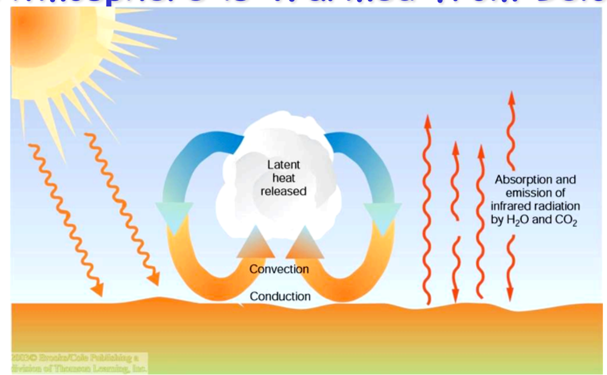
Earth's Energy Balance

Earth's annual energy balance between solar insolation and outgoing thermal radiation is achieved locally at only two latitudes

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



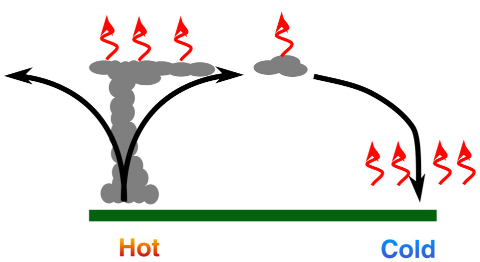
Atmosphere is Warmed from Below



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

The Job of the Atmosphere

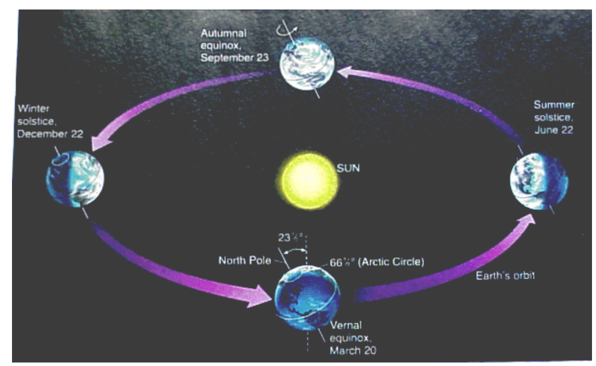
is to let the heat out!



"Piles up" in tropics "Escapes" near poles and aloft

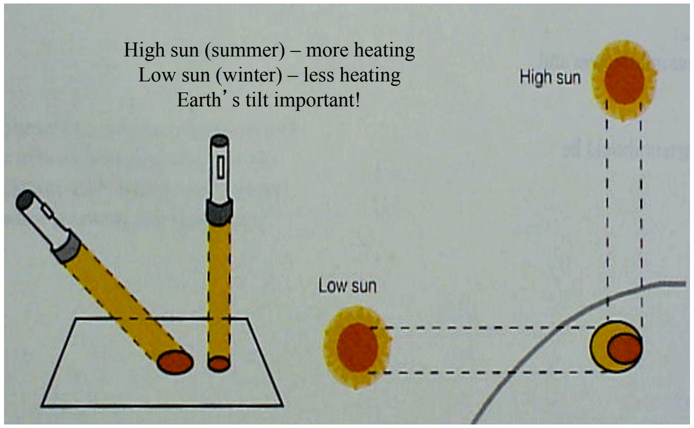
The movement of the air (and oceans) allows energy to be transported to its "escape zones!"

The Earth's Orbit Around the Sun

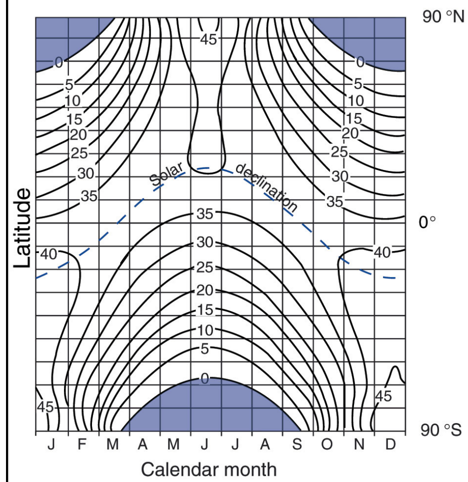


- Seasonally varying distance to sun has only a minor effect on seasonal temperature
- The earth's orbit around the sun leads to seasons because of the tilt of the Earth's axis

Smaller angle of incoming solar radiation: the same amount of energy is spread over a larger area



Daily Sunshine at Top of Atmosphere



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

Questions to Think About

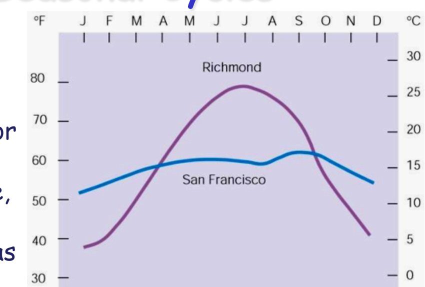
- Since polar latitudes receive the longest period of sunlight during summer, why aren' t temperatures highest there?
- Why aren' t temperatures highest at the summer solstice?
- What would happen if we changed the tilt of the earth?
  - Would we get a more/less pronounced seasonal cycle in the NH if the tilt was increased?
  - What would happen if the tilt was 90 degrees? 0 degrees?

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 °C	SAN FRANCISCO °F	RICHMOND °C	RICHMOND °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

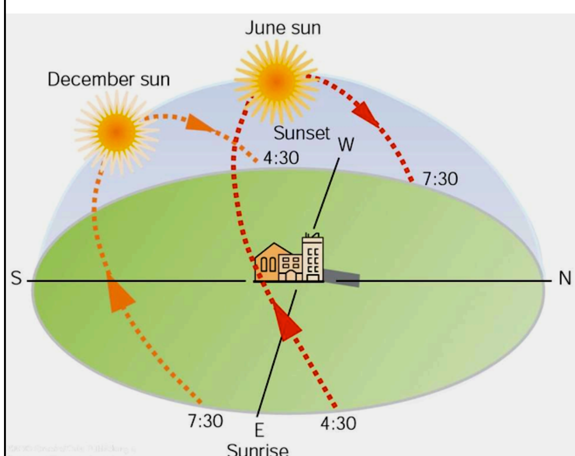
Daily Temperature Variations

- Each day is like a mini seasonal cycle
  - Sun rays most intense around noon
  - As is the case with the seasons, the maximum temperatures lag the peak incoming solar radiation.
- An understanding of the diurnal cycle in temperature requires an understanding of the different methods of atmospheric heating and cooling:
  - Radiation
  - Conduction
  - Convection

What Controls Daily High Temperatures?

- T_{max} depends on
  - Radiation (Cloud cover)
  - Surface type
    - Absorption characteristics
      - Strong absorbers enhance surface heating
    - Vegetation/moisture
      - Available energy partially used to evaporate water
  - Wind
    - Strong mixing by wind will mix heated air near ground to higher altitudes

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

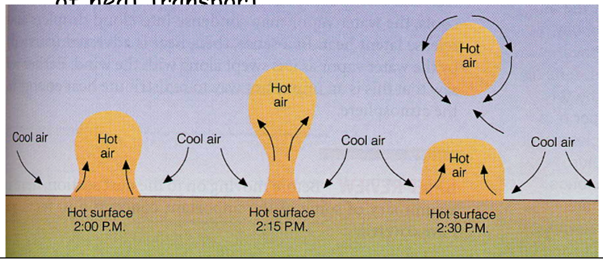
Landscape Solar Response

South facing slopes receive greater insolation, providing energy to melt snow sooner and evaporate more soil moisture.

North and south slope terrain exposure often lead to differences in plant types and abundance.

Atmospheric Heating by Convection

- Sunlight warms the ground
- Ground warms adjacent air by conduction
  - Poor thermal conductivity of air restricts heating to a few cm
- Hot air forms rising air "bubbles" (thermals) leading to convection … heats the air, but cools the surface!
  - Mechanical mixing due to wind enhances this mode of heat transport



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.