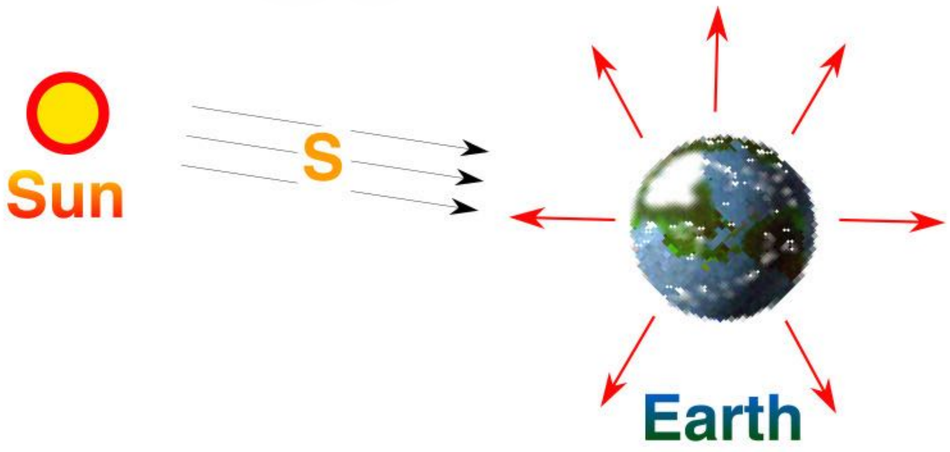
How Climate Works

Module 3

Temperature of a Planet

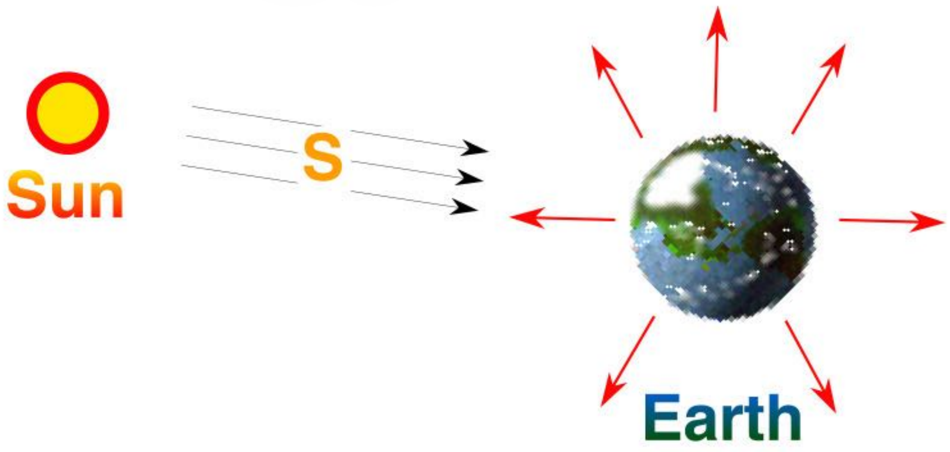
Energy Balance



Energy In = Energy Out

- Let the rate of energy flow from the Sun to the Earth be called F_{in}
- Let the rate of energy flow from the Earth to outer space be called F_{out}

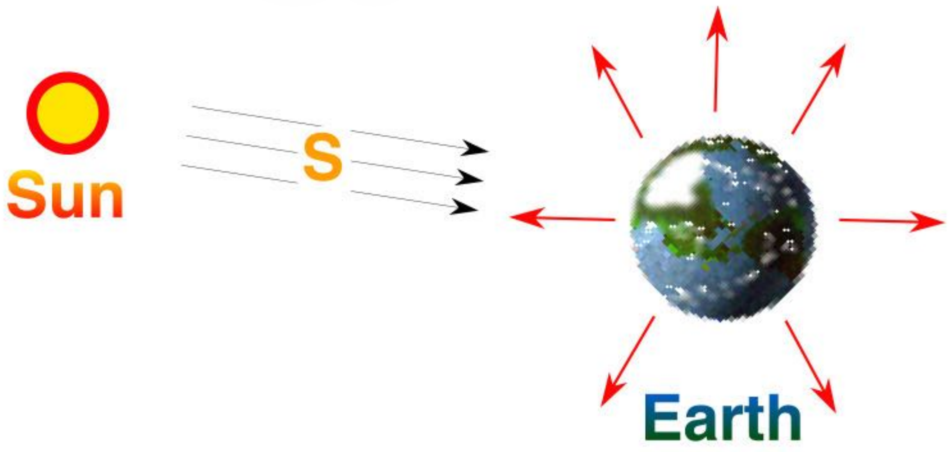
Energy Balance



$$F_{in} = F_{out}$$

- Assume both Sun and Earth are blackbodies (ε=1), so $F = \sigma T^4$
- F_{in} = absorbed sunlight x daylight area
- $F_{out} = \sigma T_{earth}^4$ x total area

Energy Balance

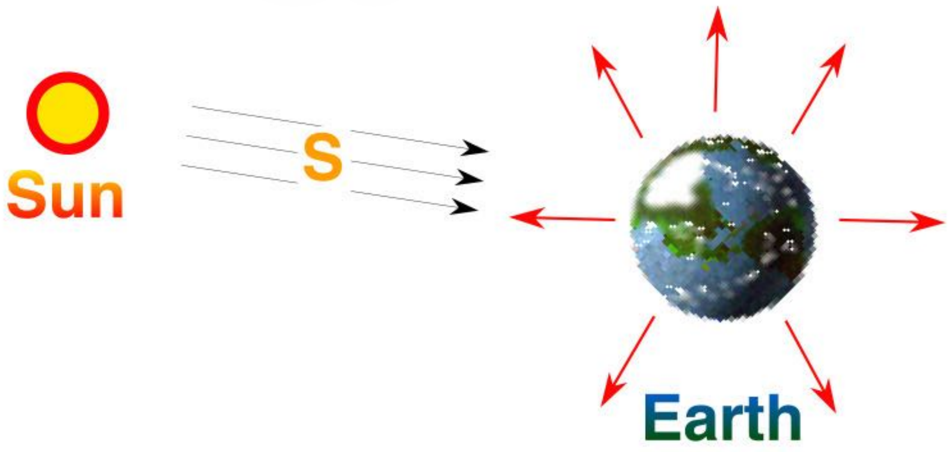


$$F_{in} = F_{out}$$

F_{in} = Solar brightness x (1 – albedo)
x (area of Earth's shadow)

F_{out} = $\sigma\,(T_{earth})^4$ x (area of Earth's surface)

Energy Balance

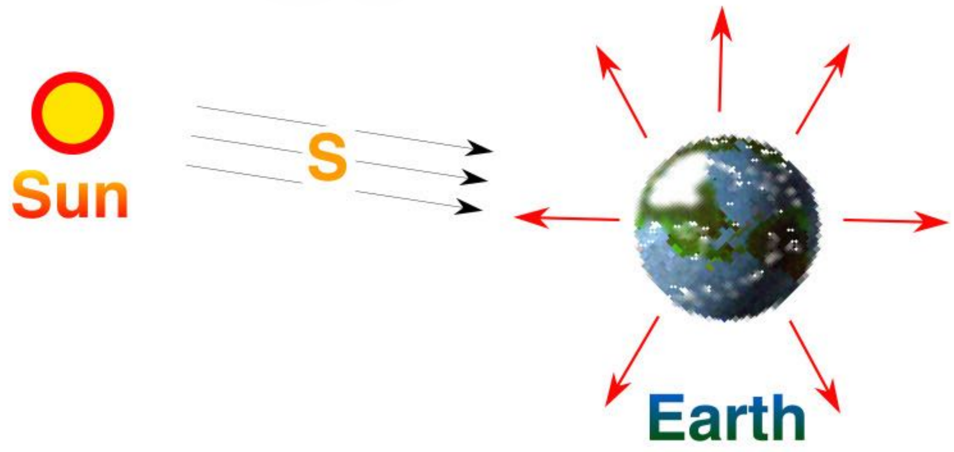


$$F_{in} = F_{out}$$

$$F_{in} = \text{Solar brightness} \times (1 - \alpha) \times \pi r^2$$

$$F_{out} = \sigma (T_e)^4 \times 4\pi r^2$$

Energy Balance



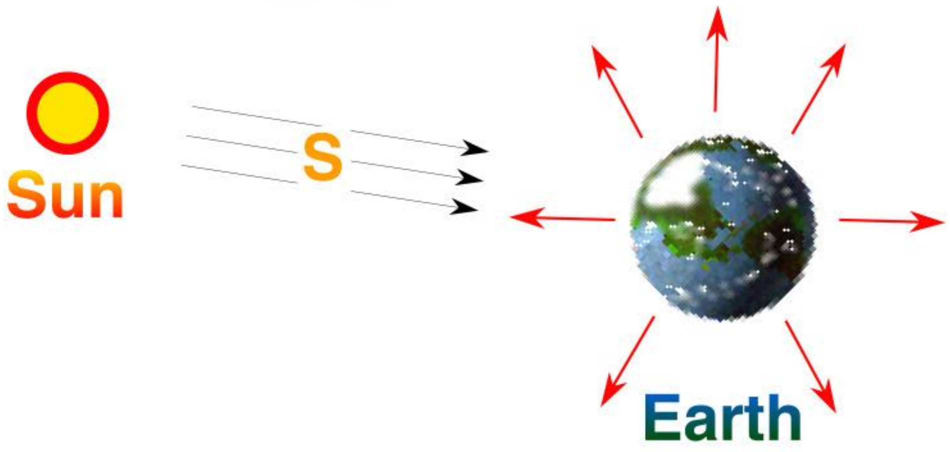
F_{in} = F_{out}

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

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

$$\frac{S(1-\alpha)}{4\sigma} = T^4$$

Energy Balance

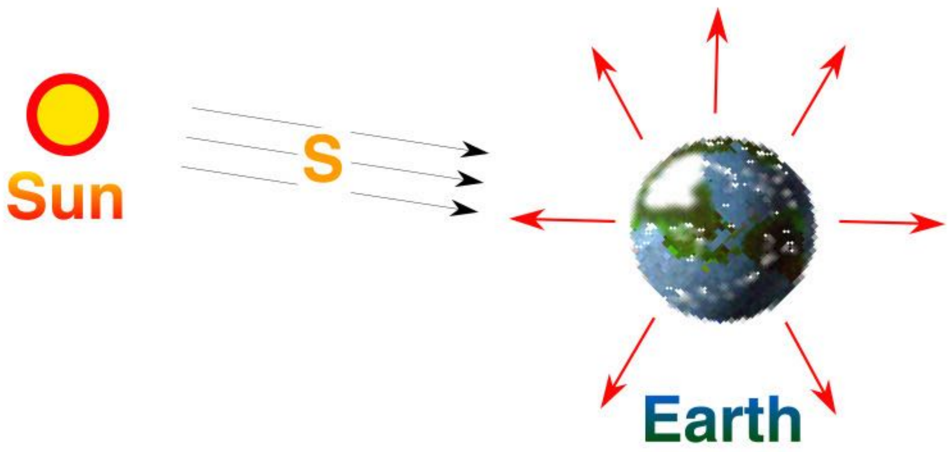


$$F_{in} = F_{out}$$

$$T = \left(\frac{S(1-\alpha)}{4\sigma}\right)^{1/4} = \left(\frac{(1360\,Wm^{-2})(1-0.3)}{4(5.67x10^{-8}\,Wm^{-2}K^{-4})}\right)^{1/4} = 255K$$

But the observed
surface temperature is about 288 K

Works for Other Planets Too



F_{in} = F_{out}

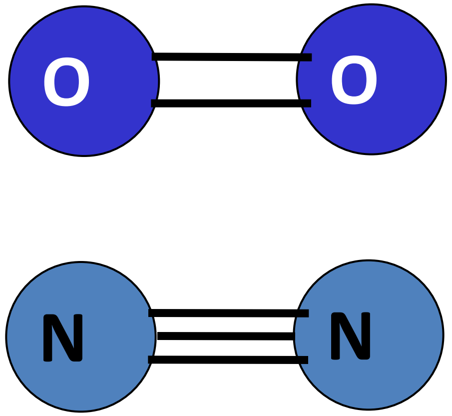
$$\frac{S(1-\alpha)}{4\sigma} = T^4$$

Experiment! http://tinyurl.com/planetary-balance

Greenhouse Effect

Dancing Molecules & Heat Rays!

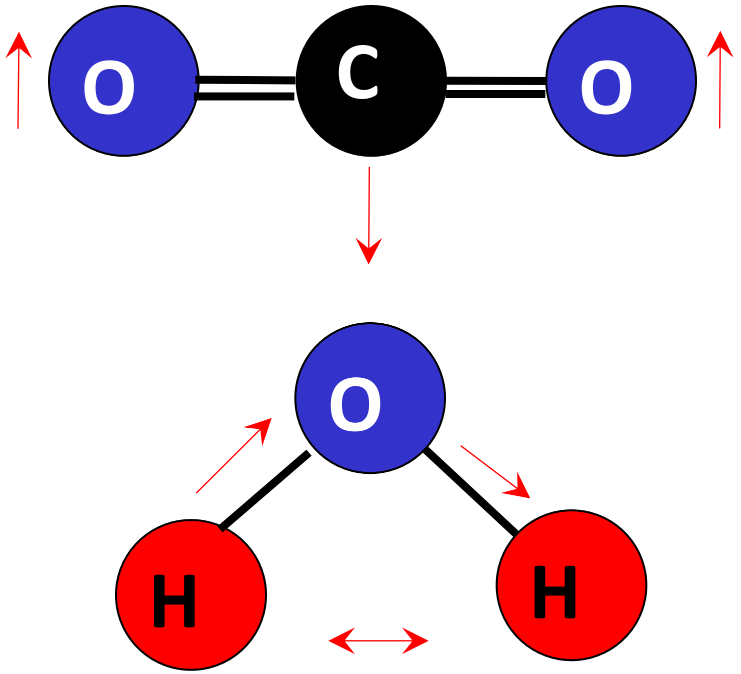
- Nearly all of the air is made of oxygen (O_2) and nitrogen (N_2) in which two atoms of the same element share electrons
- Infrared (heat) energy radiated up from the surface can be absorbed by these molecules, but not very well



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

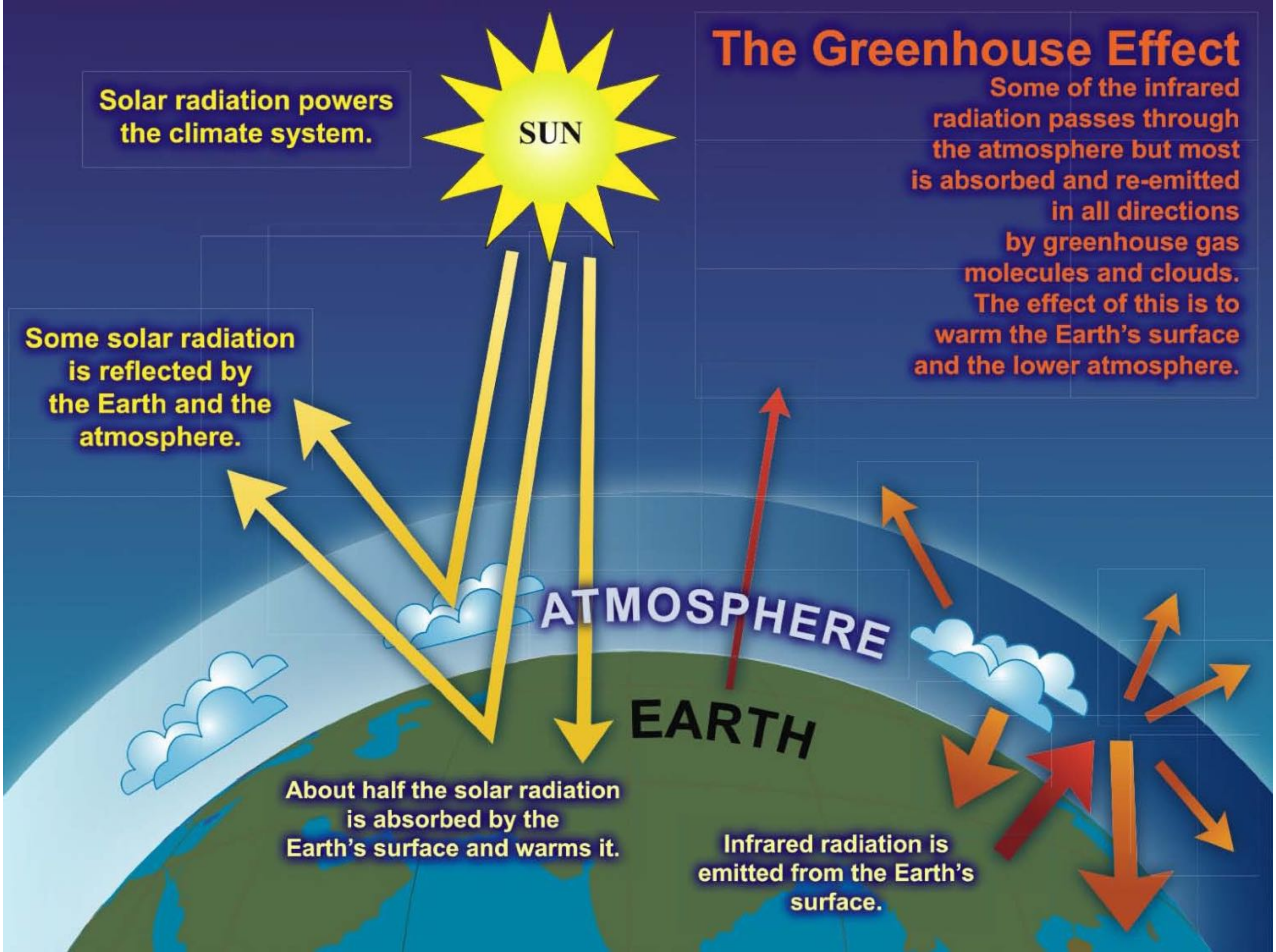
Dancing Molecules & Heat Rays!

- 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

Absorption spectrum of CO_2 was first measured 1863


The Greenhouse Effect
Solar radiation powers the climate system.
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.
ATMOSPHERE
EARTH
About half the solar radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

Bathtub Analogy

- If faucet runs faster than drain, level rises

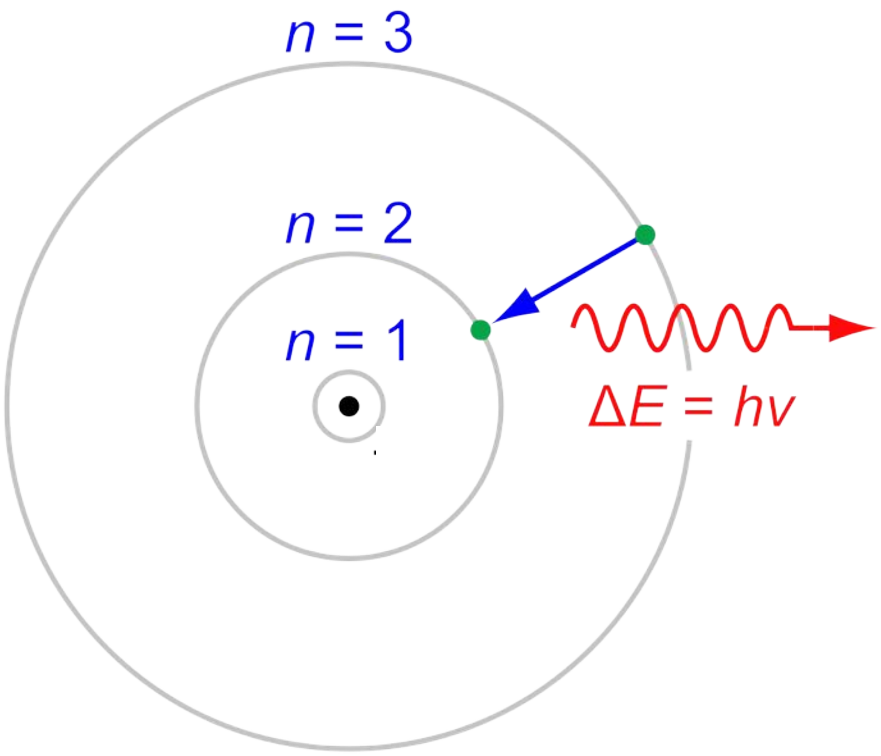
  … and vice versa
- Drain runs faster when water is deep
- Adding CO_2 to air acts like a clog in the drain
- Water rises until drainage balances inflow again

Faucet ~ Sunshine
Drain ~ Thermal emission
Water level ~ temperature

Greenhouse Gases

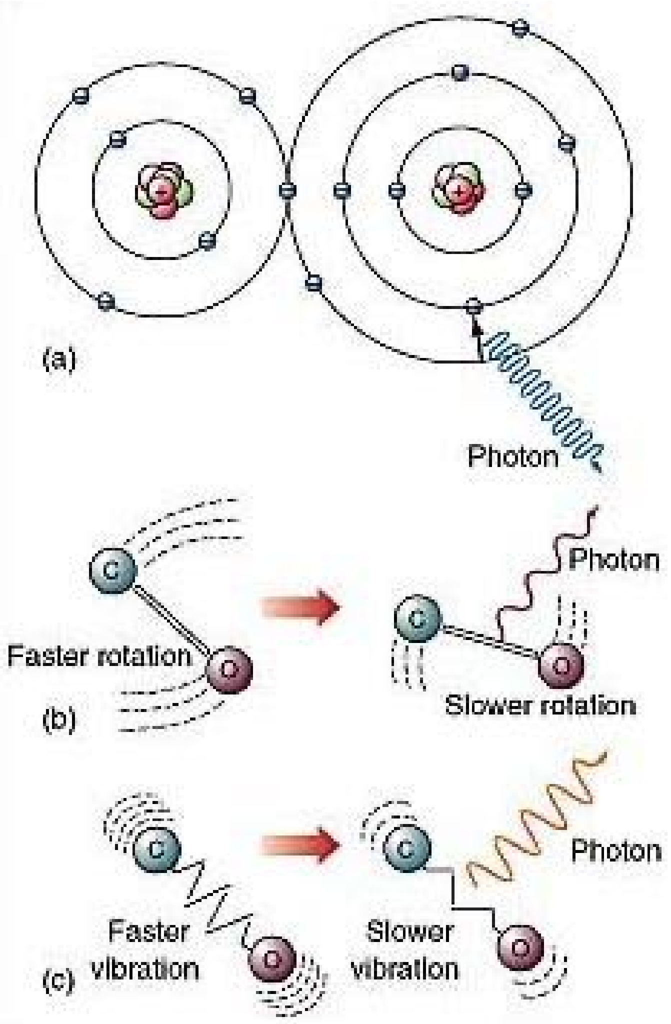
Energy is "Quantized"

- When radiation interacts with atoms and molecules, only certain "jumps" in energy are possible
- Electrons orbit at specific energy levels above an atomic nucleus
- Absorption of a photon of just the right energy can make them "jump up" to the next level



- Emission of a photon occurs when an electron "falls" down to a level below

Molecules and Photons

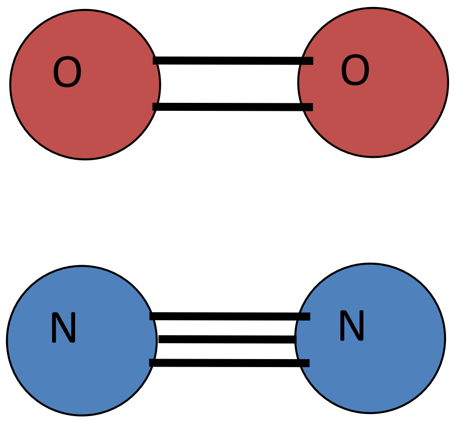


- Molecules are groups of atoms that share electrons (chemical bonds)
- Molecular transitions involve changes in vibration, rotation, bending, and stretching of chemical bonds
- Photons can interact with molecules to change states
- Transitions involve specific amounts of energy, so only certain wavelengths are active

Molecular transitions typically absorb & emit in thermal infrared

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



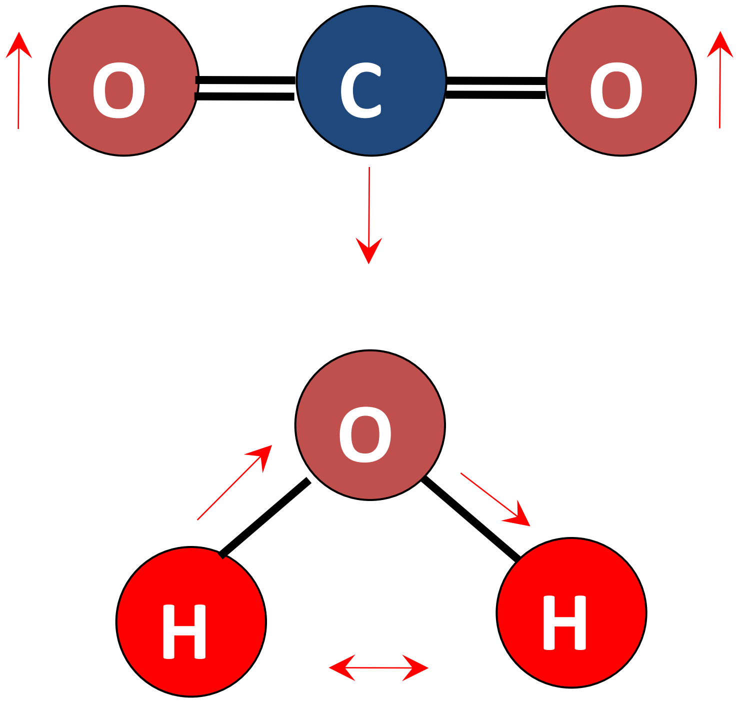
- Infrared (heat) **energy radiated up from the surface can be absorbed** by these molecules, but not very well

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

No electric dipole!

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

Optical "Thickness"

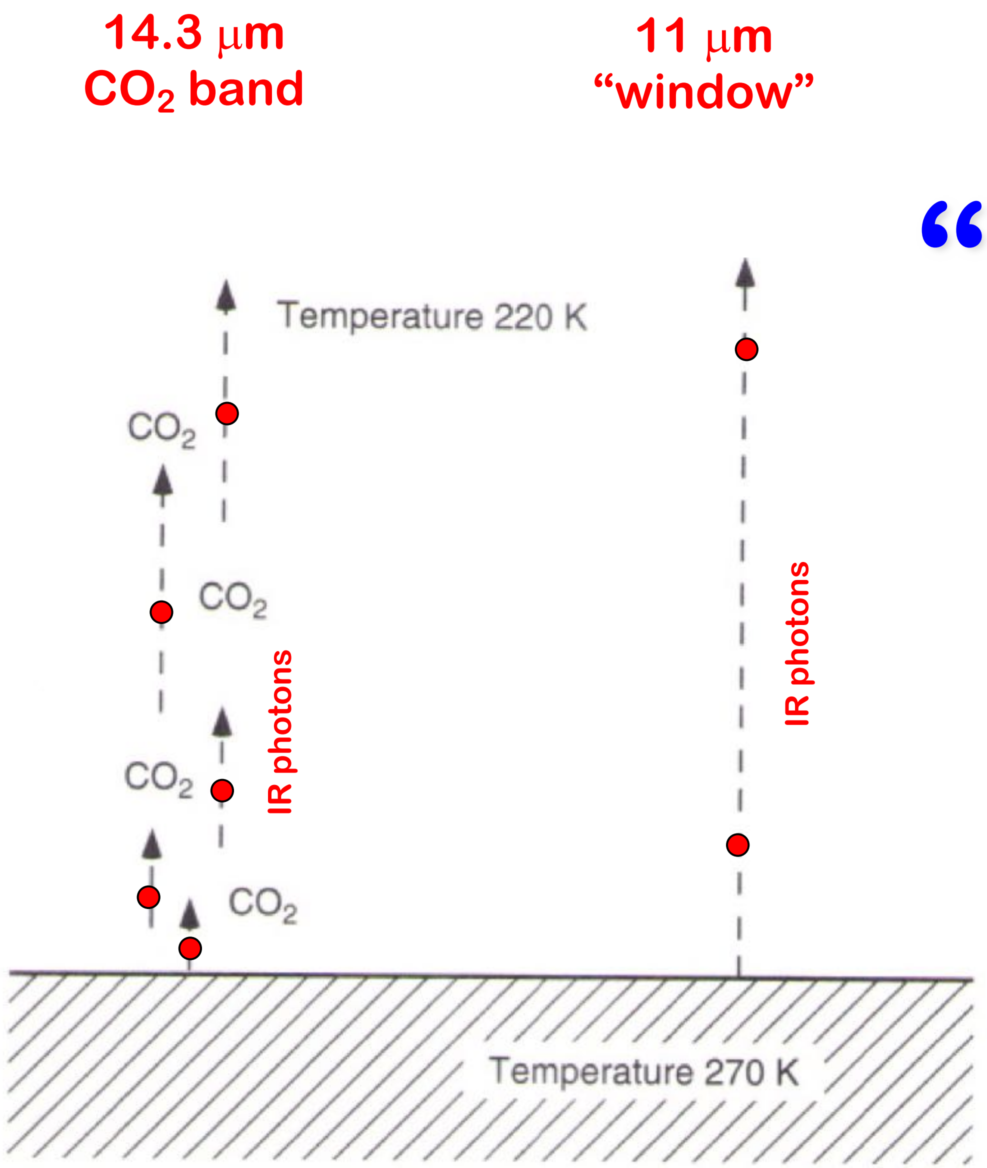
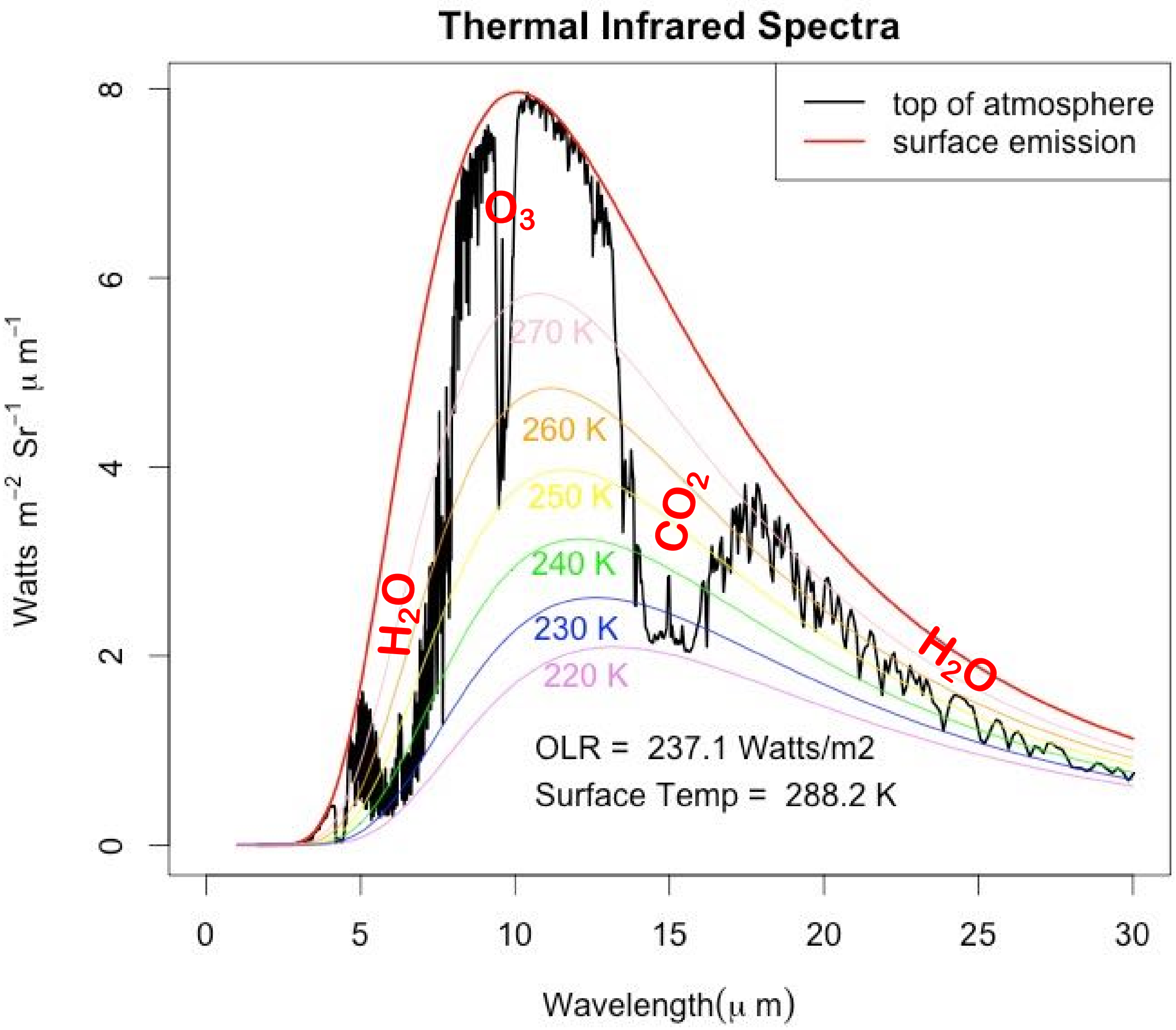


Figure 4-4 A comparison of the fate of infrared light in the optically thick CO_2 bend frequency (*left*) versus the optically thin atmospheric window (*right*).

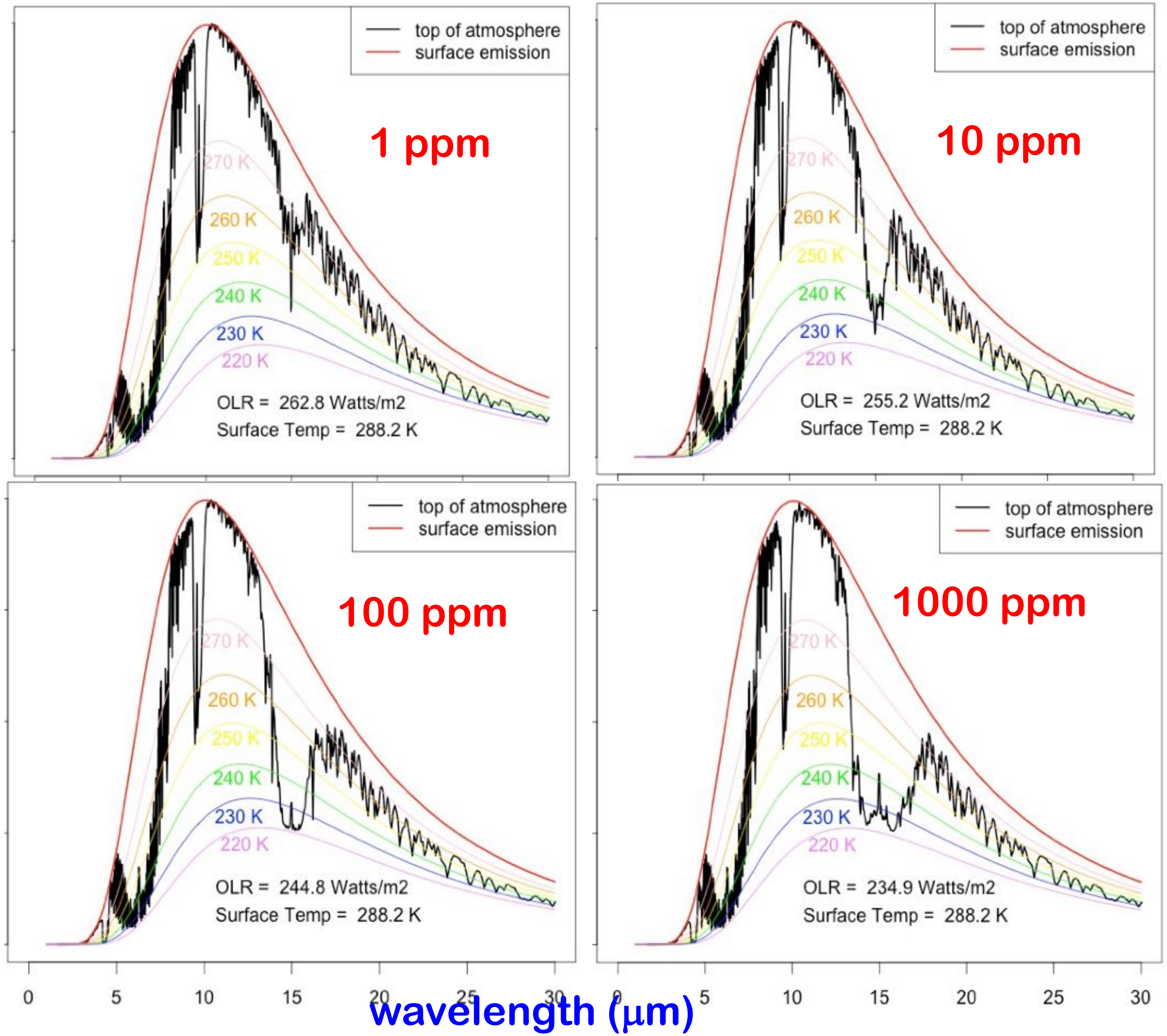
- In CO_2 absorption bands, atmosphere is **totally opaque to IR photons**
- They get absorbed **and re-emitted higher up**
- It's **cold up there!**
- Think about the Layer Model

View from Space

- Hot surface emits directly to space in window region
- Cold upper layers emit to space in optically thick regions
- Total emission much less than from sfc



Effect of Adding CO_2

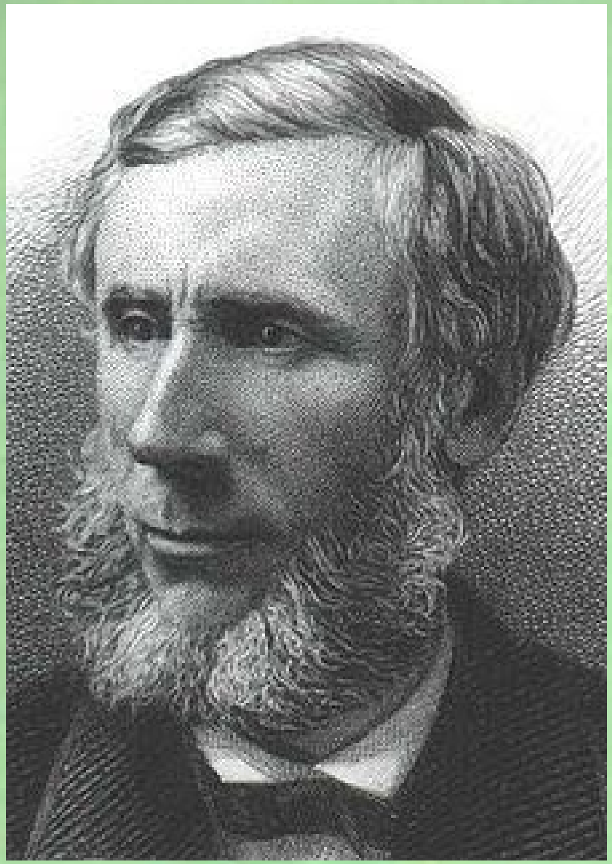


- Optically thick regions are as cold as they can get
- But the thick regions get wider with added CO_2
- Rate of total emission (area under black curve) decreases less and less

Radiative *Forcing* by Increased CO_2

- An instantaneous doubling of CO2 reduces outgoing infrared by 3.7 Watts per square meter if temperature stays constant
- As temperature gradually rises, more infrared emission results
- Eventually, outgoing infrared increases to balance absorbed sunlight again, but with higher temperatures

Common Sense

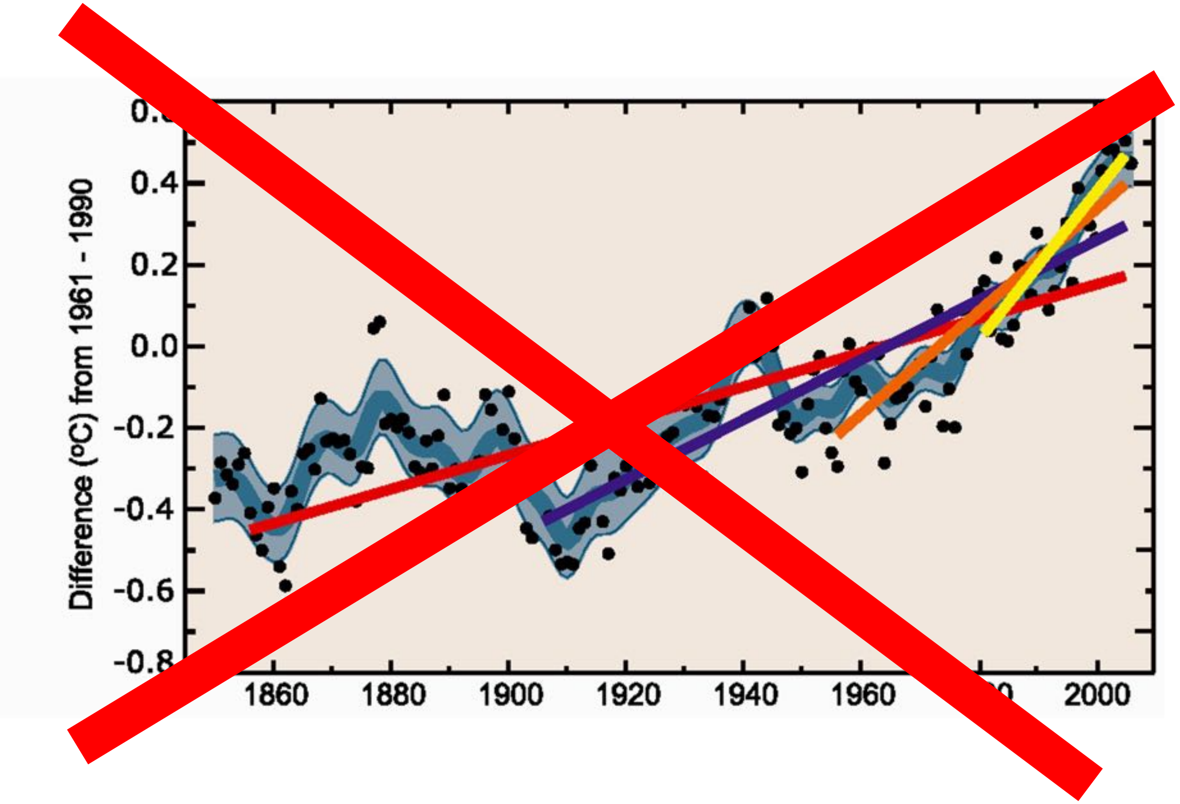


John Tyndall, January 1863

- Doubling CO_2 would add 4 watts to every square meter of the surface of the Earth, 24/7
- Doing that would make the surface warmer
- This was known before light bulbs were invented!

Common Myth #1

"Scientists think burning coal causes global warming because it's been getting warmer lately"



WRONG! We're sure because we know that when we add heat to things, they warm up

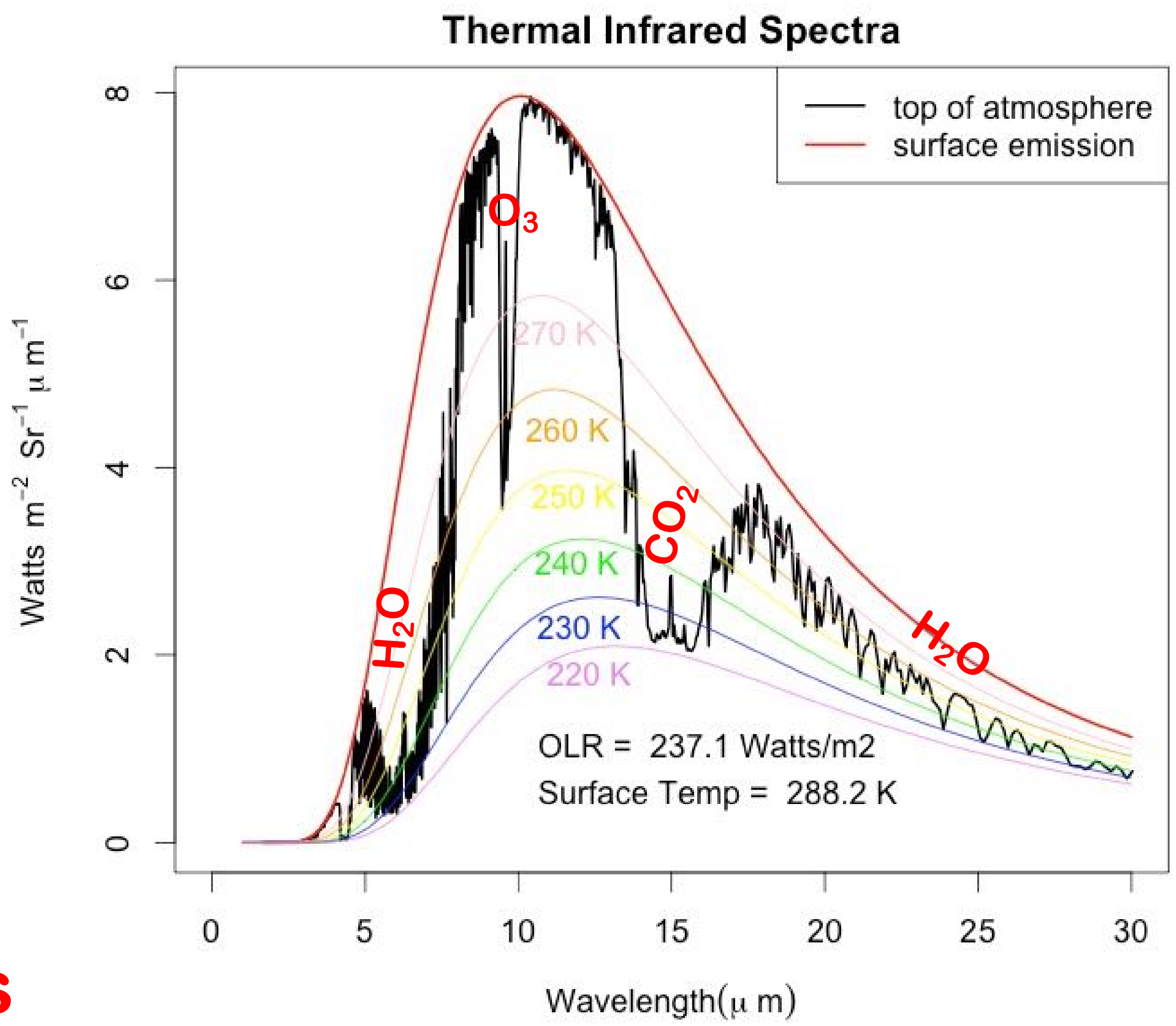
Remember

- Infrared radiation can interact with shared electrons (chemical bonds) of atmospheric gas molecules
- Less than 1% of gases in air have more than 2 atoms
- CO_2 and H_2O molecules absorb and emit many wavelengths of thermal radiation emitted by Earth
- The air is selectively transparent: visible light gets through, but infrared radiation is trapped
- Doubling CO_2 absorbs about 4 Watts of thermal energy per square meter of the whole Earth

Vertical Energy Exchange

Greenhouse Effect

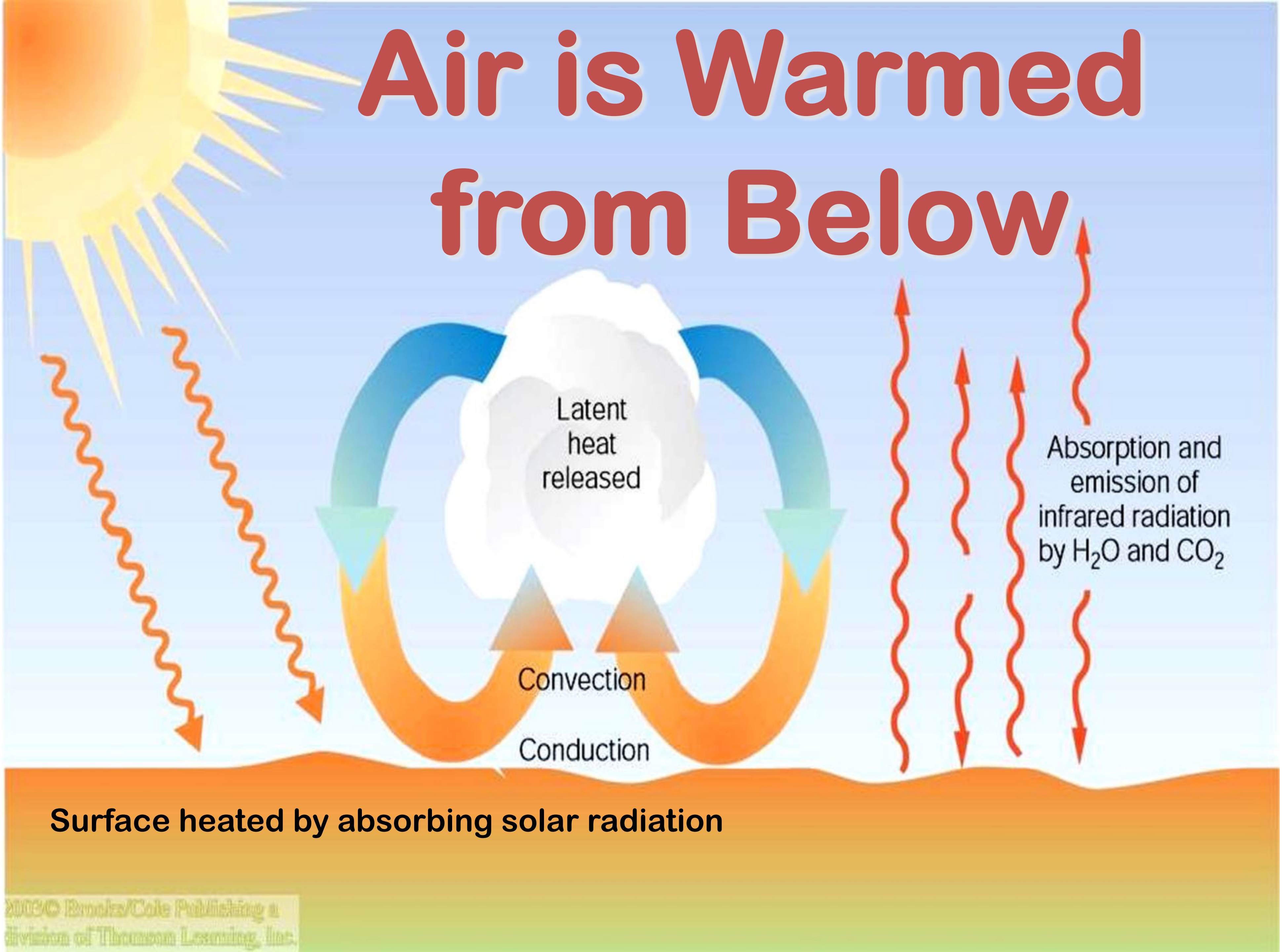
- Hot surface emits directly to space in window region
- Cold upper layers emit to space in optically thick regions



Vertical Variations are 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 Denver!
- Changes in atmospheric temperature with height are responsible for the

Air is Warmed from Below



Vertical Mixing

- Vertical mixing of the atmosphere cools the surface, and warms the upper air
- Greenhouse Effect depends on thermal radiation being emitted from the cold upper layers
- So the more vertical convective mixing we get, the less powerful the Greenhouse

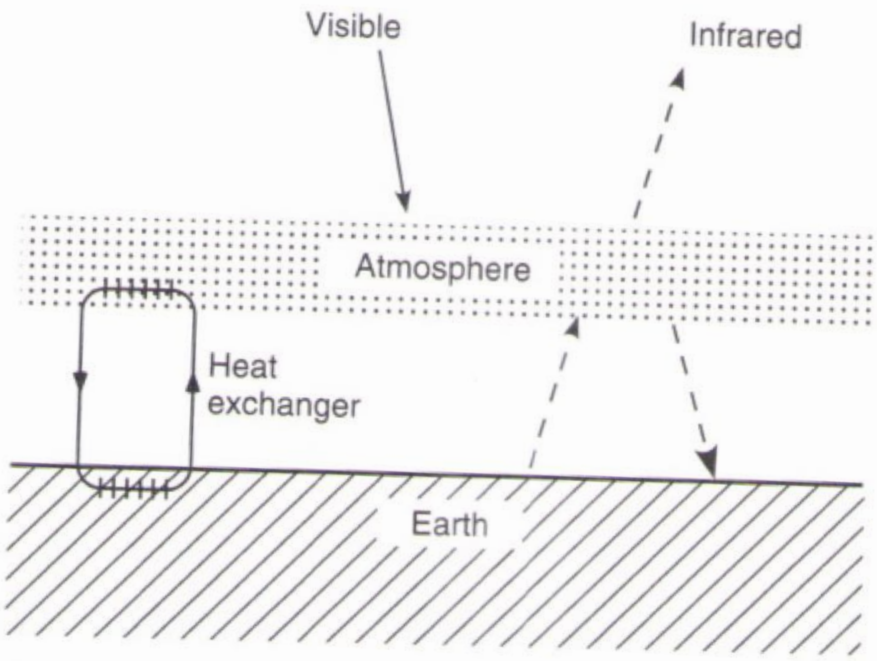
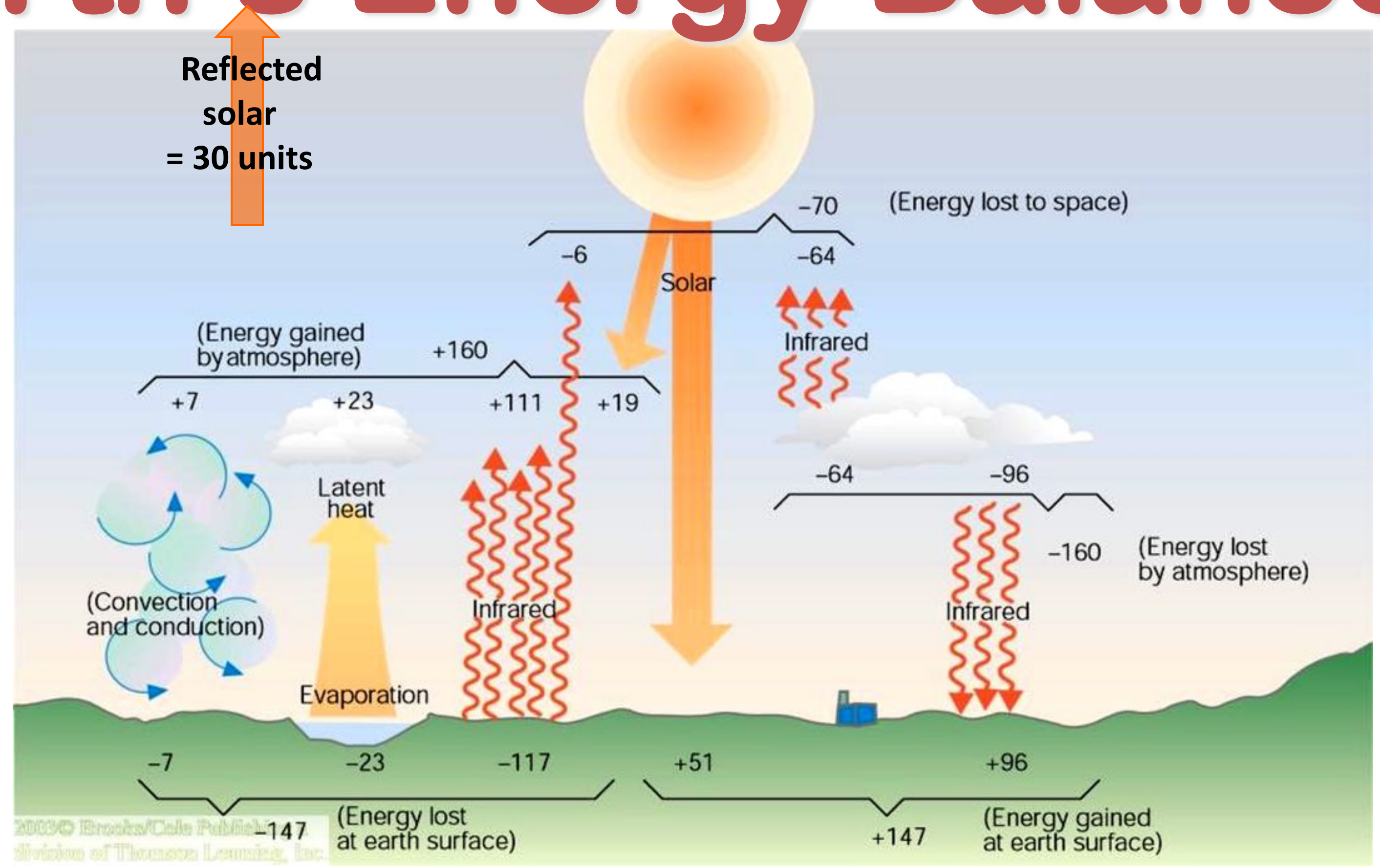


Figure 5-1 The Layer Model from Chapter 3 with an added heat exchanger, capable of partially or completely equalizing the temperatures of the two layers.

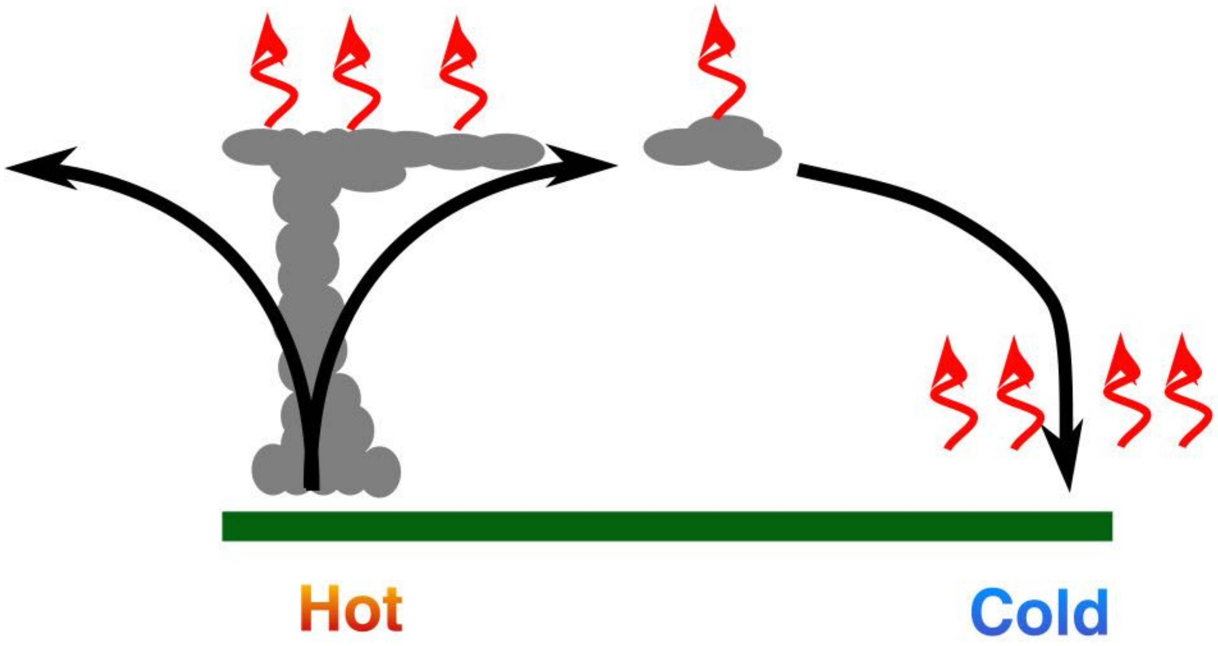
Earth's Energy Balance(s)



- 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)

The Job of the Air & Sea

is to let the energy out!



“Piles up”
in tropics

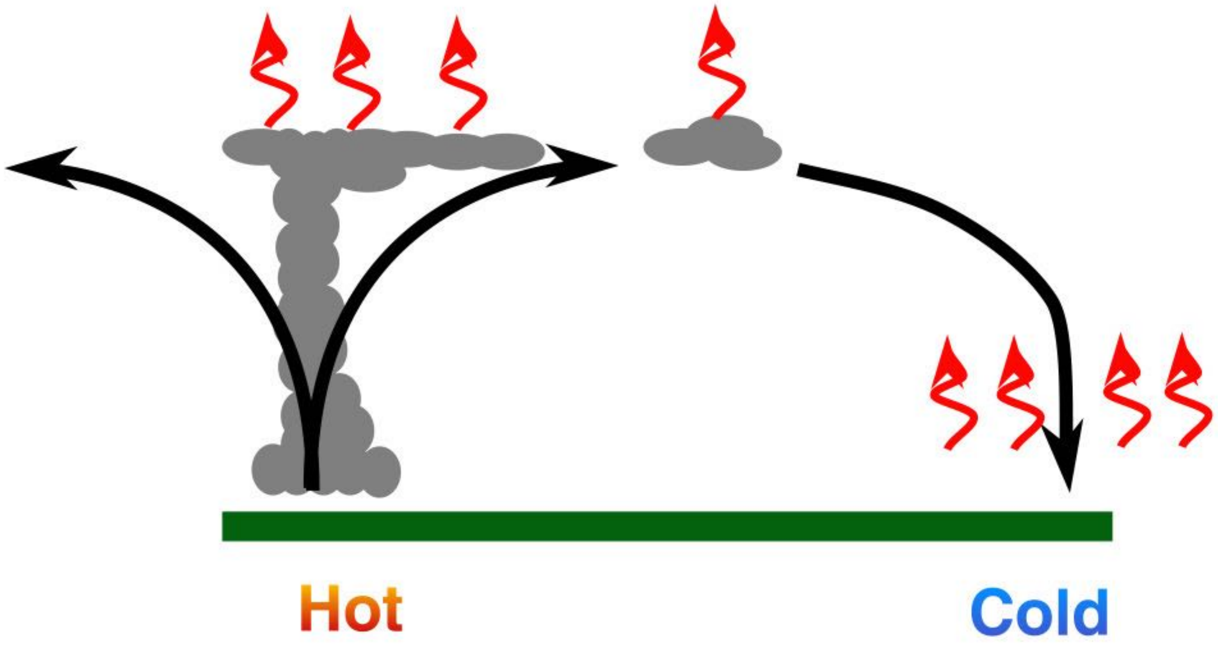
“Escapes” near
poles and aloft

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

Lateral Energy Exchange

The Job of the Atmosphere

is to let the energy out!

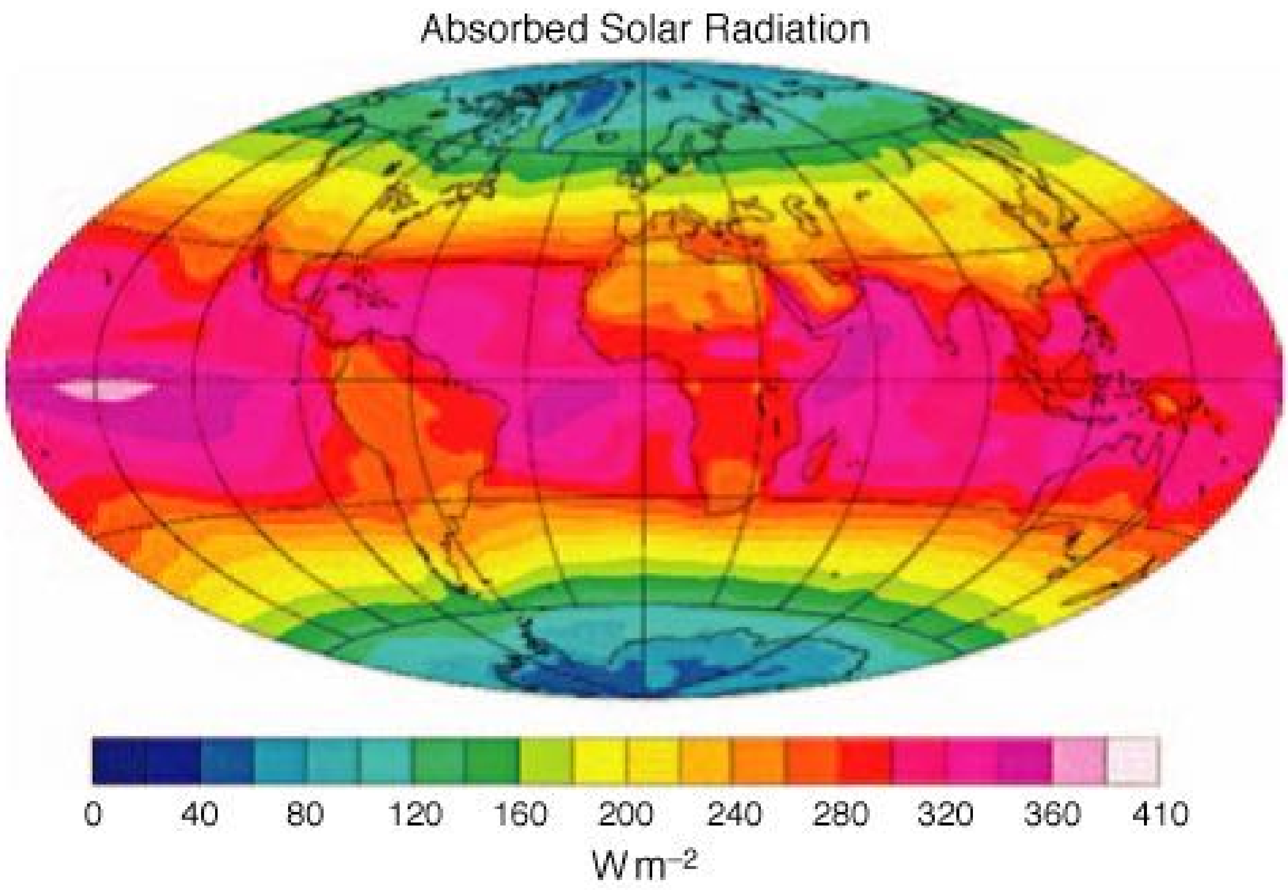


"Piles up" in tropics

"Escapes" near poles and aloft

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

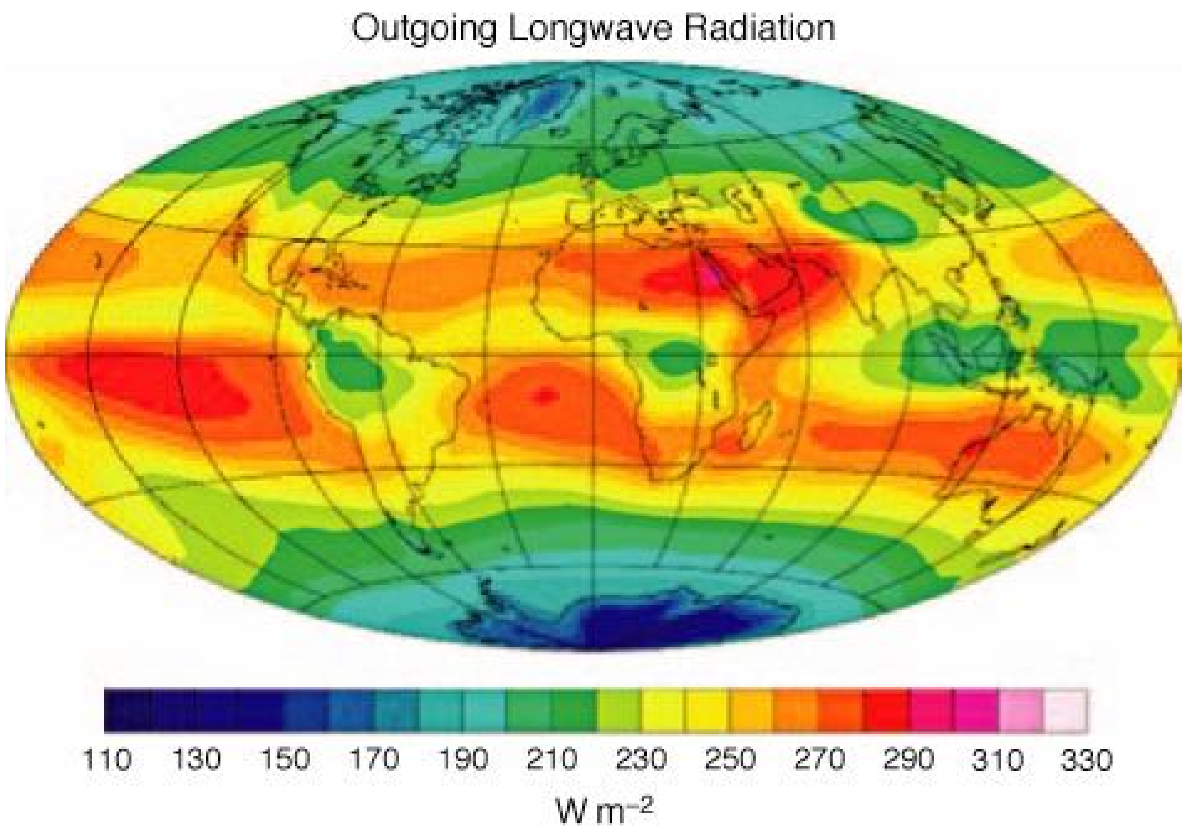
Energy In



Annual Mean

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

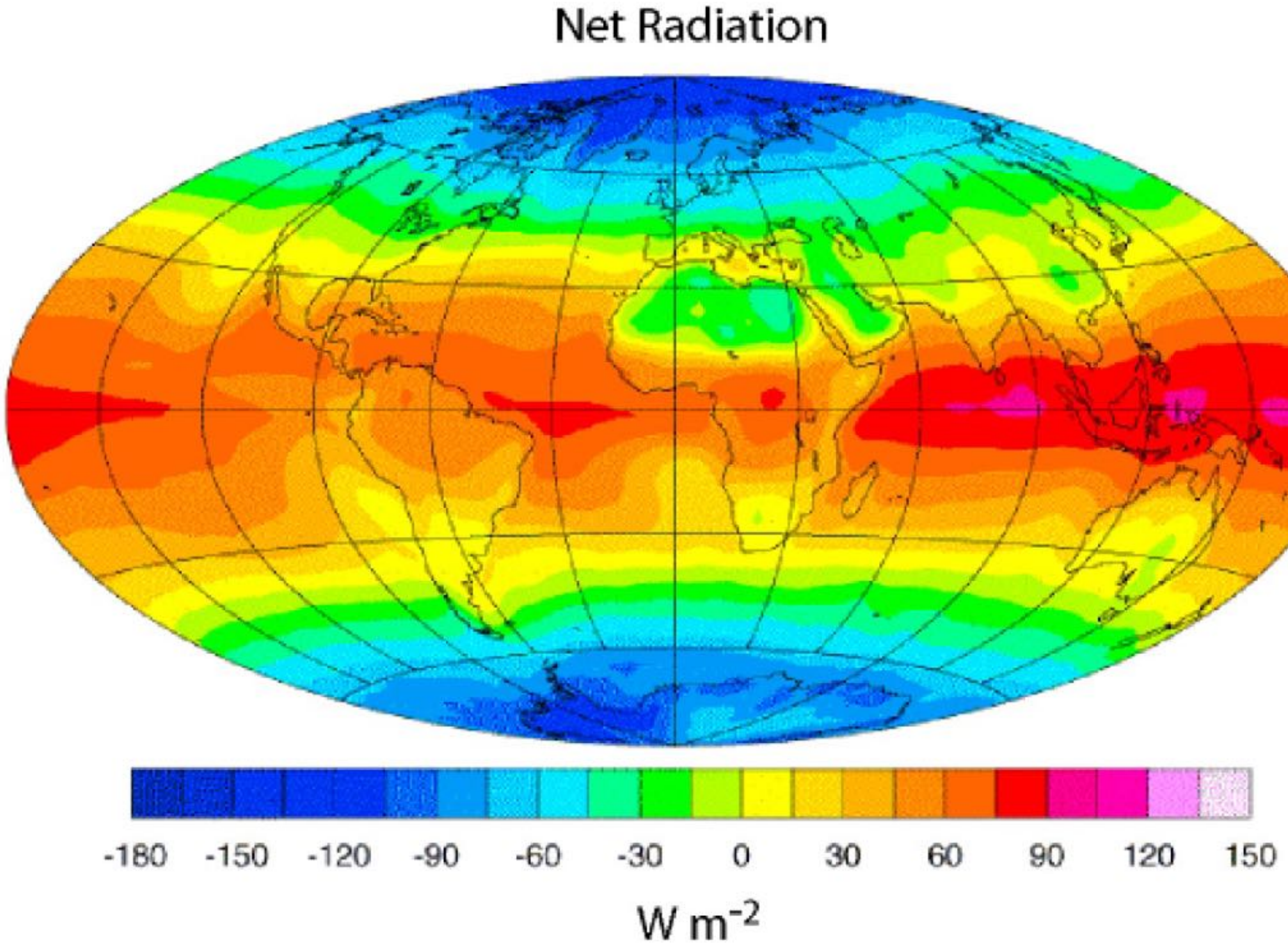
Energy Out



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, clear atmosphere)

Energy In minus Energy Out

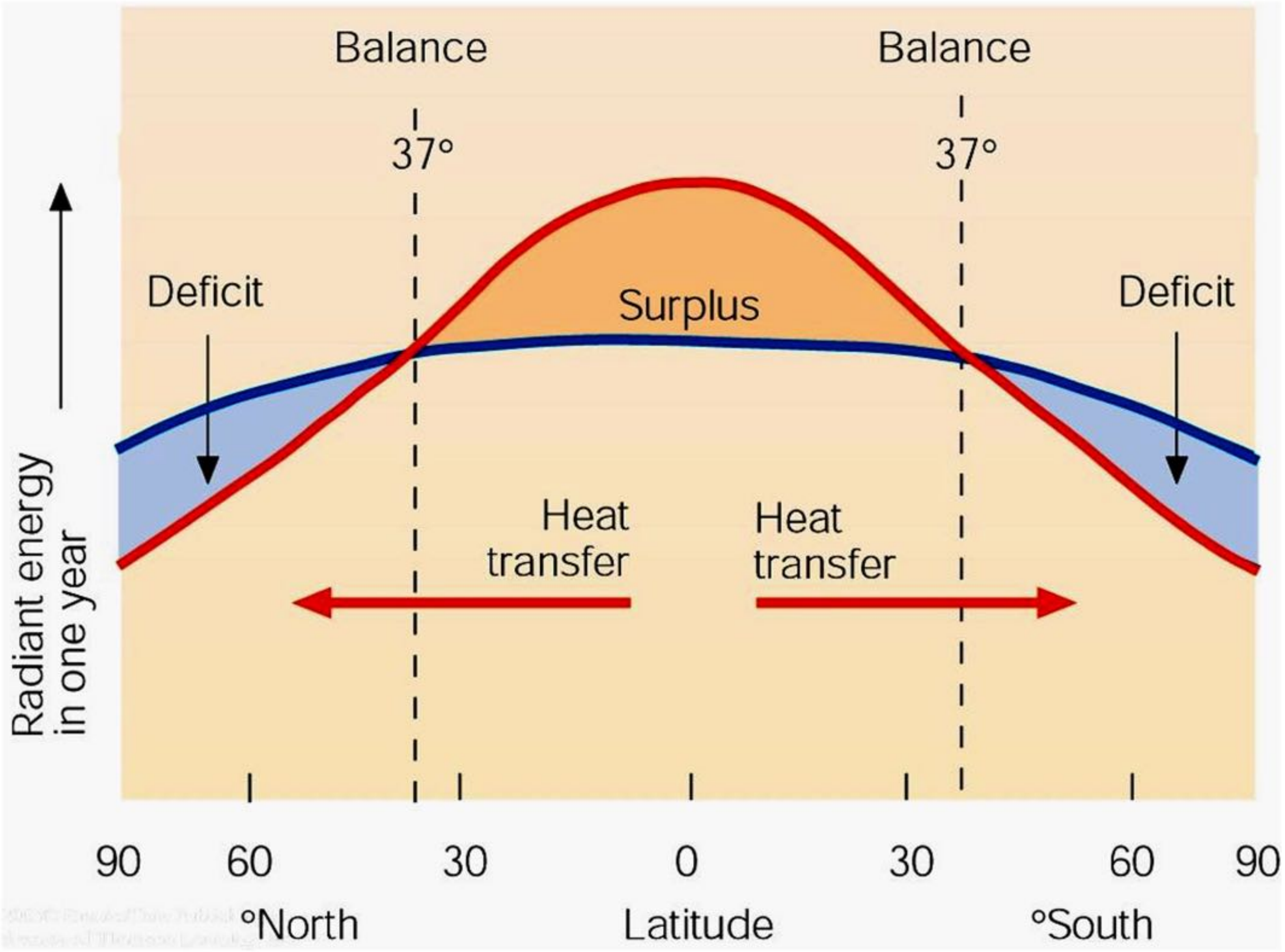


- Incoming solar minus outgoing longwave
- Must be balanced by horizontal

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

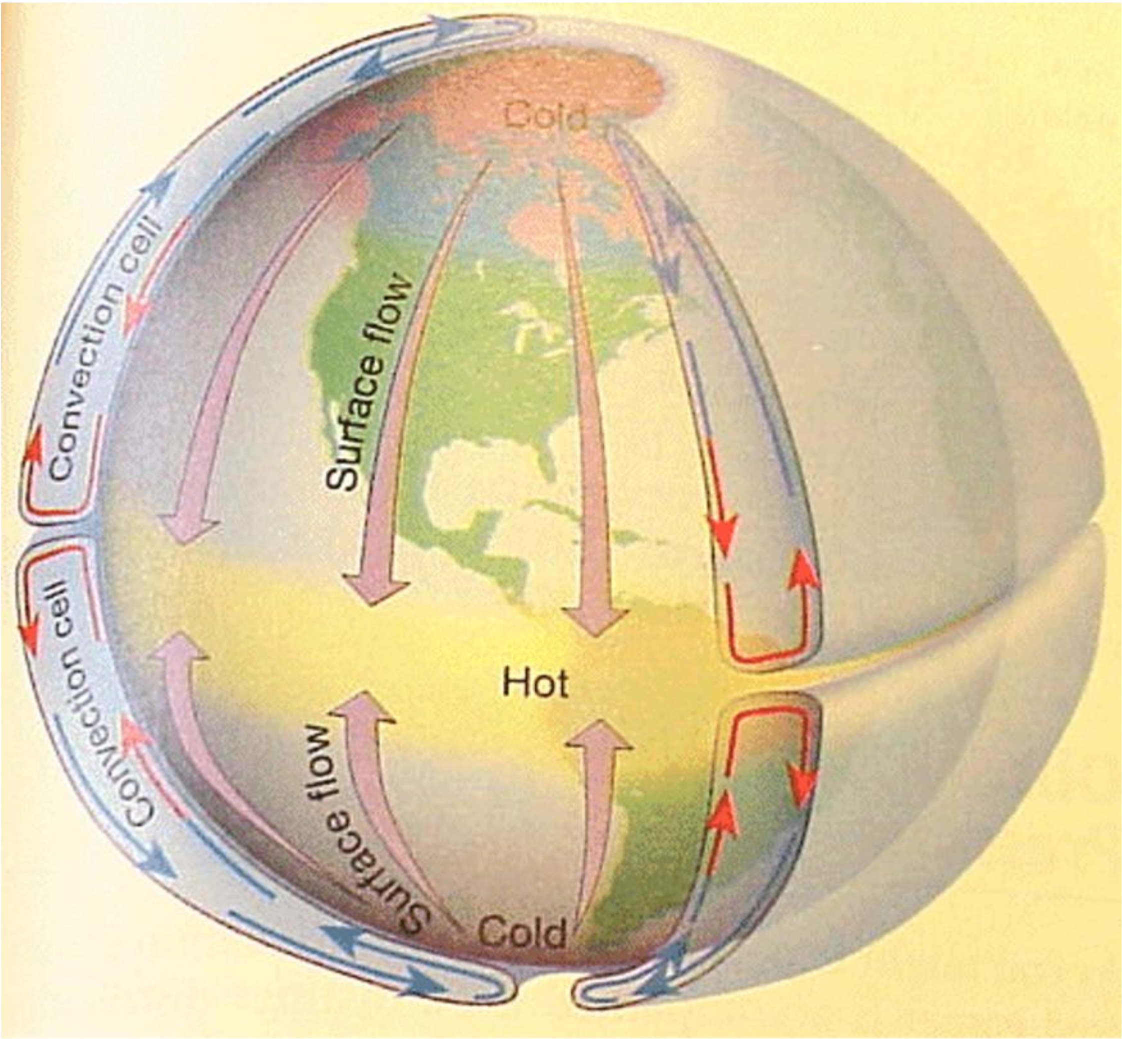


Circulation:

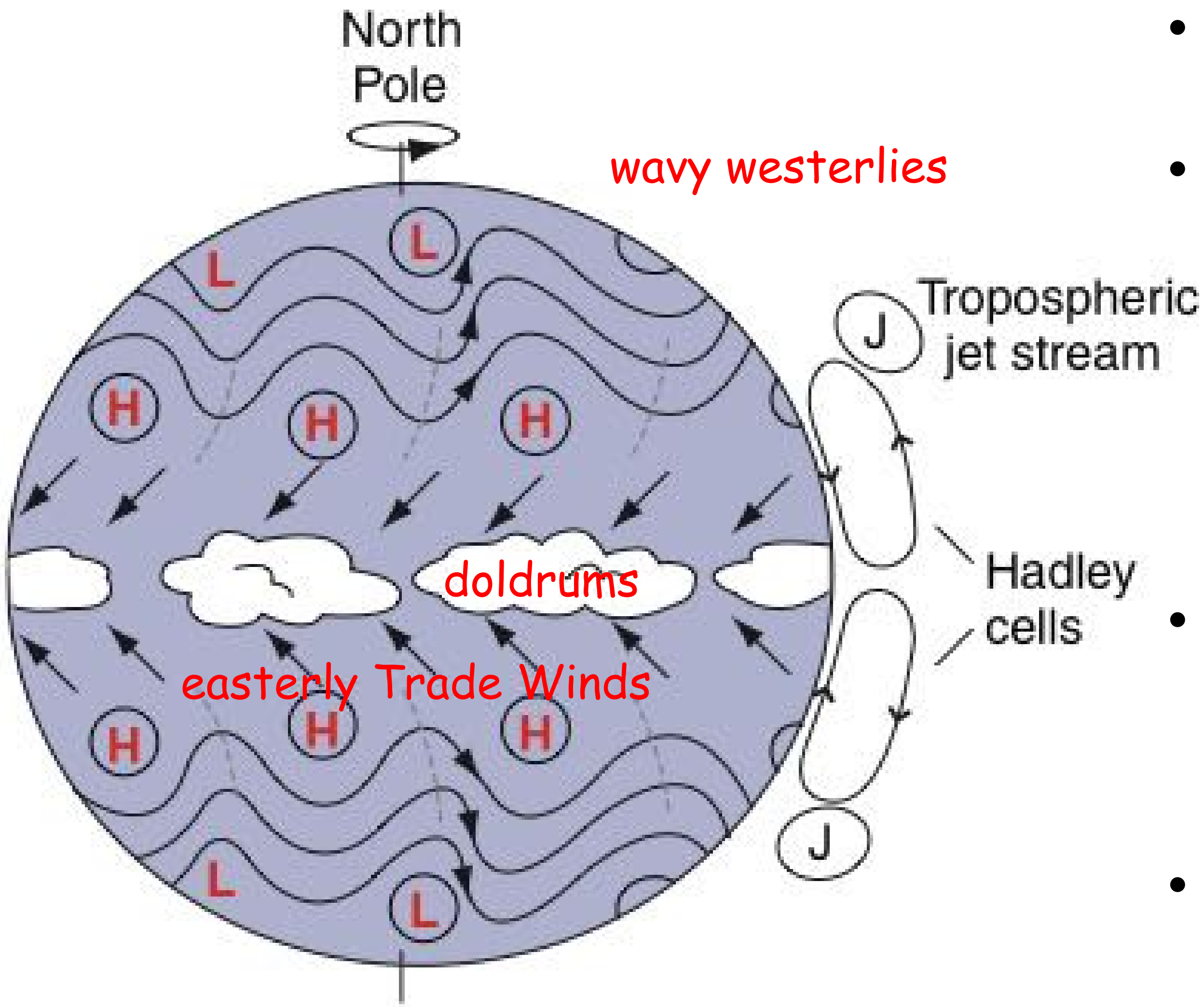
Wind & Water

If the Earth didn't rotate, it would be easy for the flow of air to balance the energy

- Thermal convection leads to formation of convection cell in each hemisphere
- Energy transported from equator toward poles
- Surface wind in Colorado would always blow from the North



Winds on the Rotating Earth

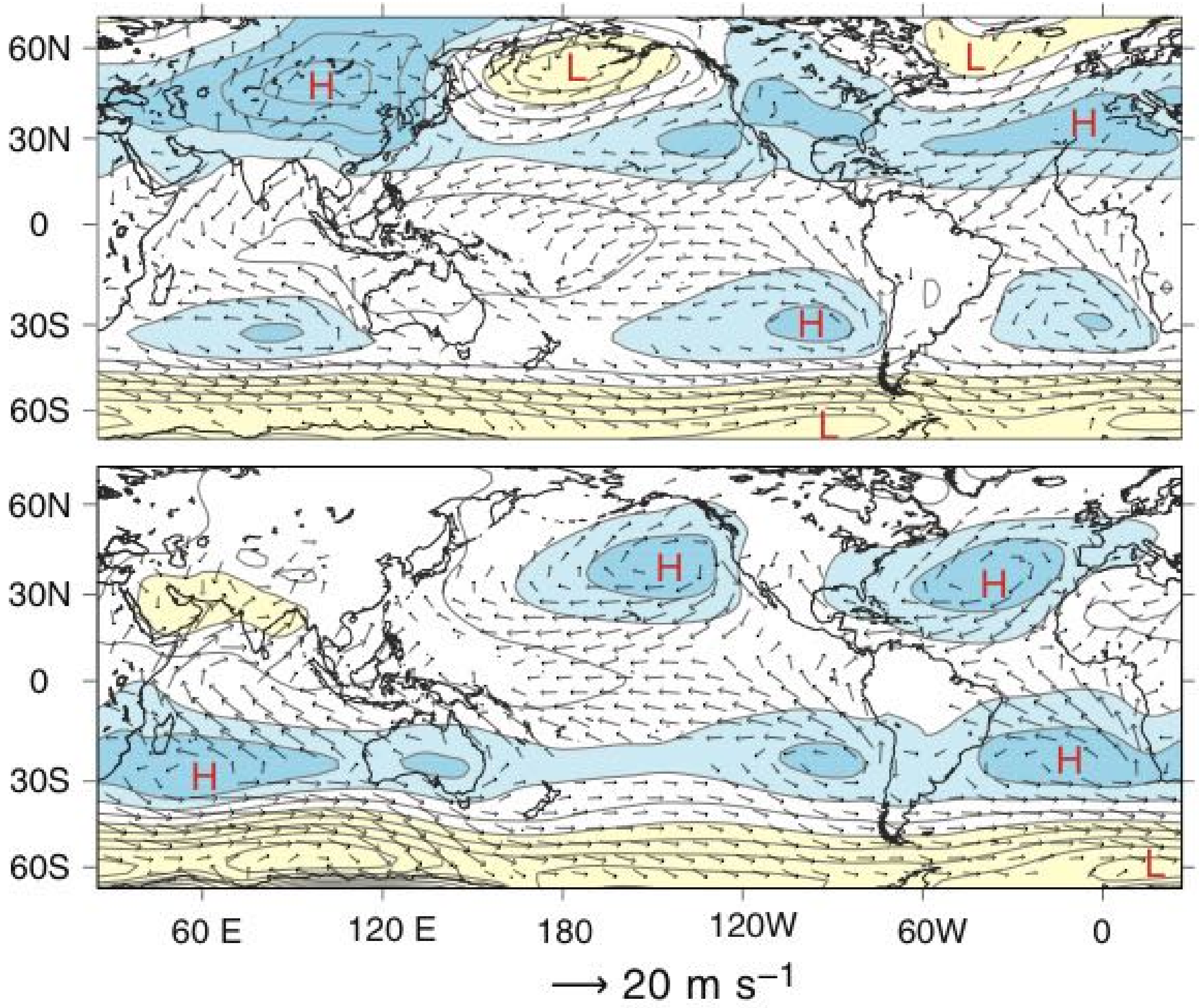


- Deep convective cells confined to tropics
- Condensation heating in rising branch of Hadley Cell lifts the center of mass of the atmosphere (converts latent to potential energy)
- Downhill slope toward winter pole produces jet streams in middle latitudes
- Jet is unstable to small perturbations, breaks down in waves we call winter storms

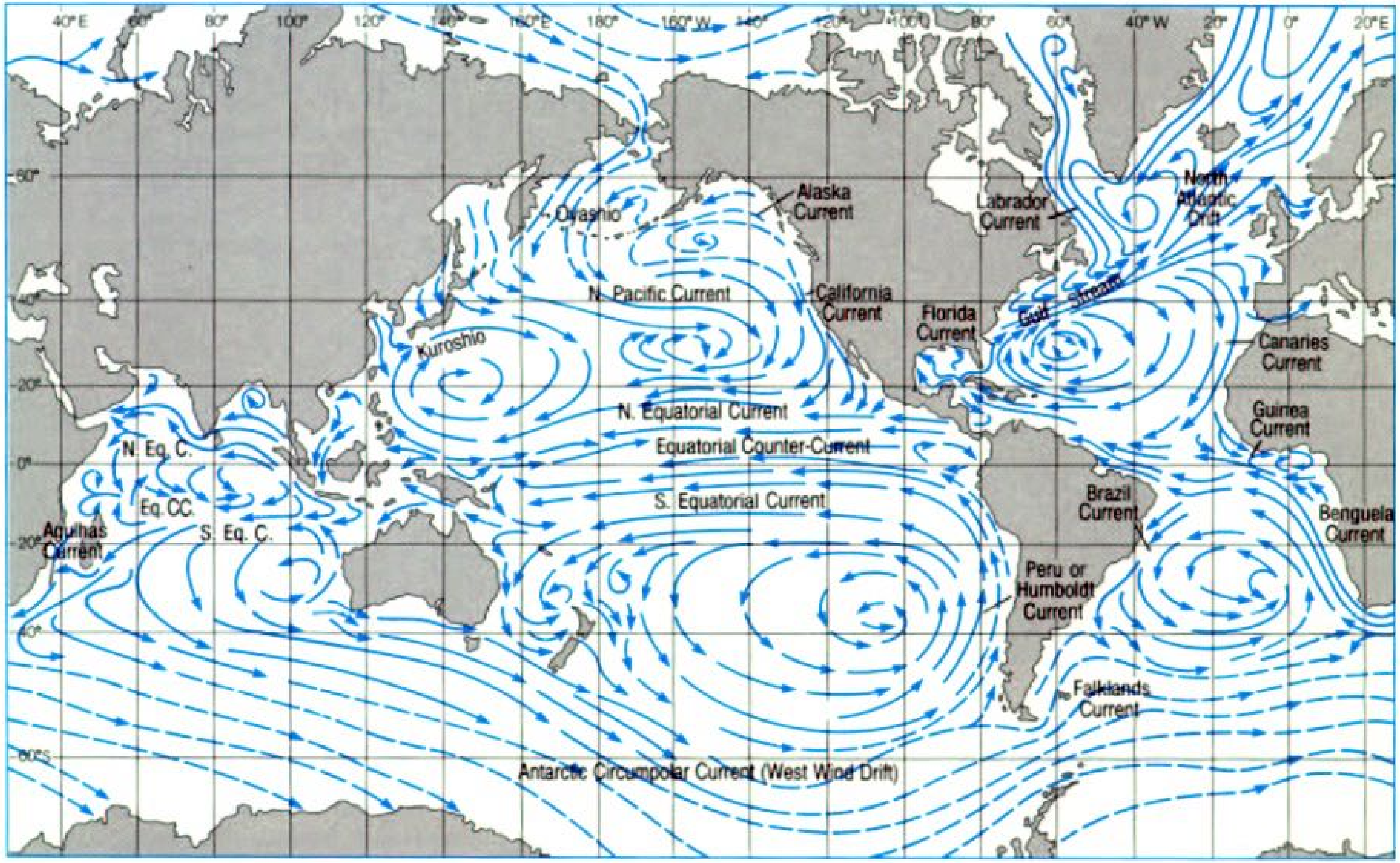
Surface Winds and Pressure

January

July

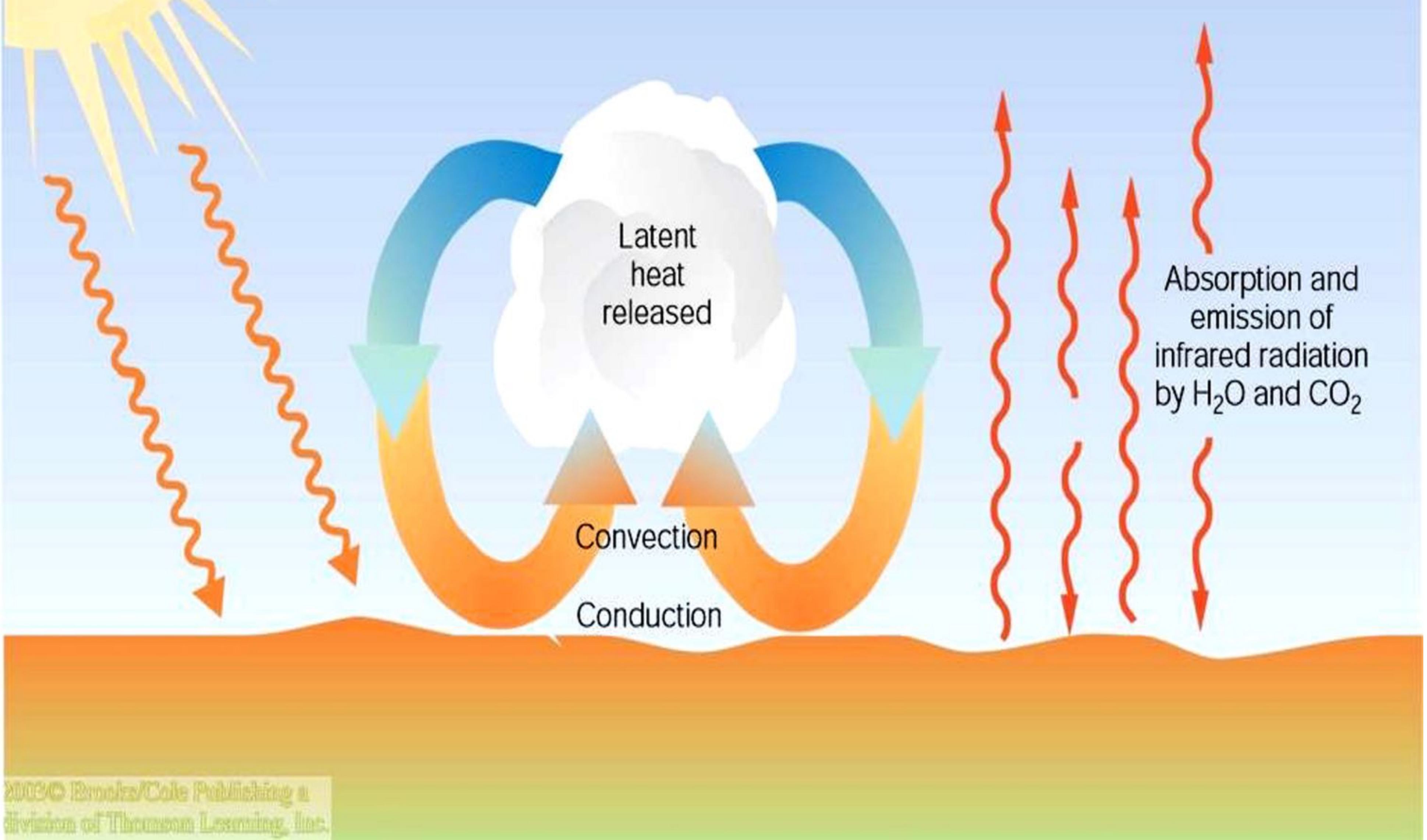


Ocean Currents

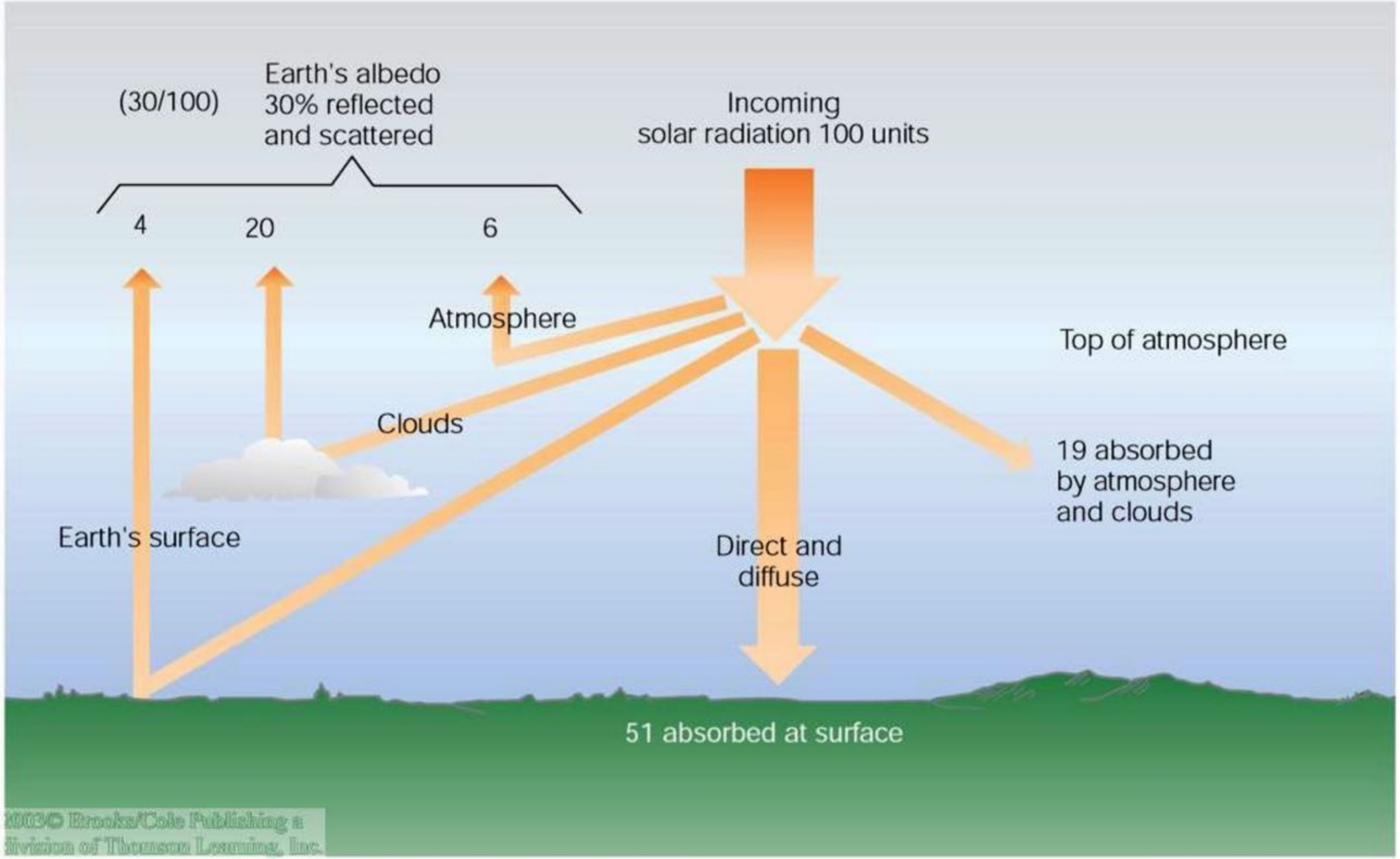


Surface Energy Exchange

Atmosphere is Warmed from Below



Solar Radiation



- 30% reflected by clouds, air, dust, and surface
- 19% absorbed by the atmosphere (mostly clouds)
- 51% absorbed at the surface

Reflection

- Albedo: the fraction of incoming radiation that gets reflected

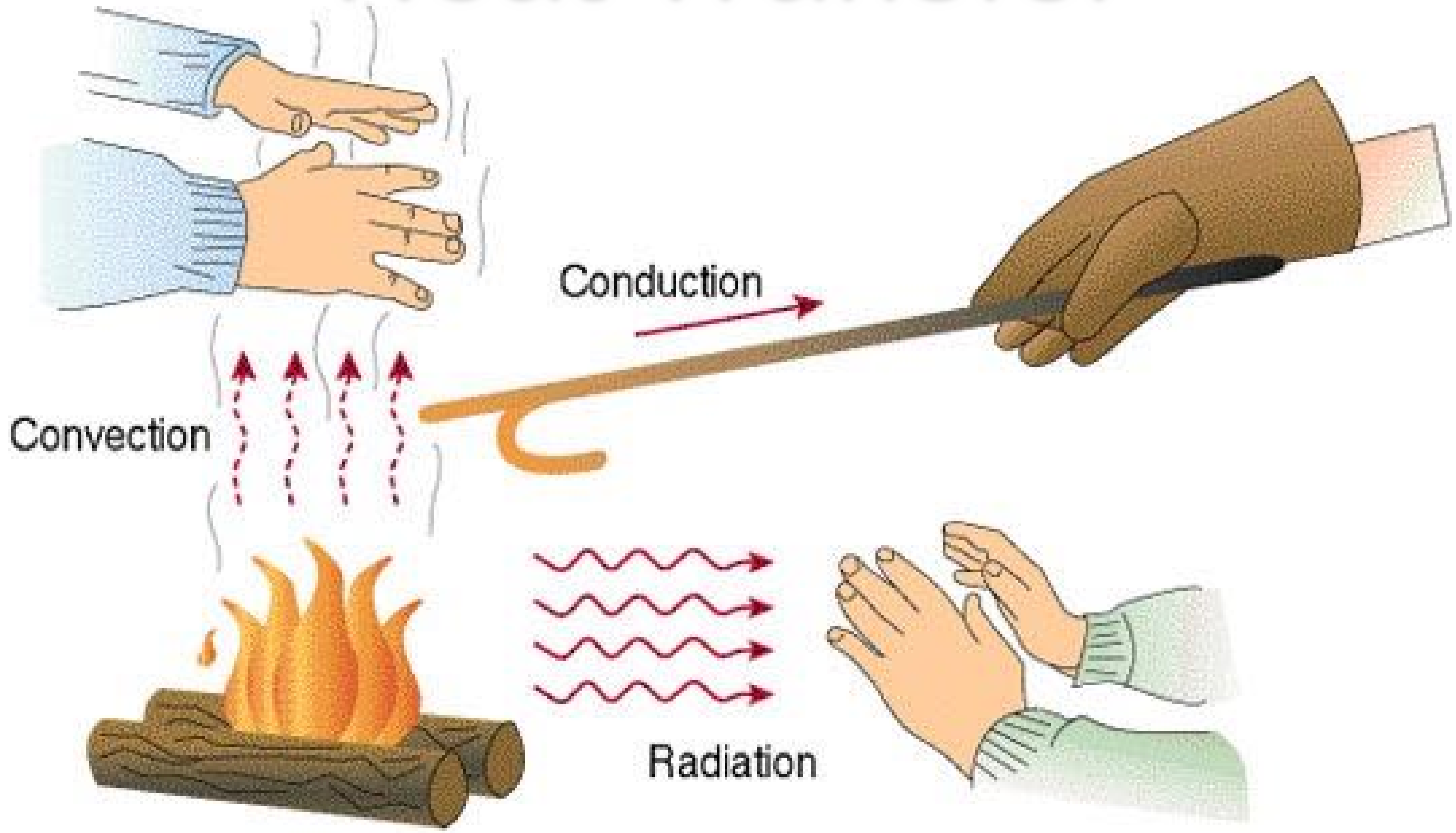
- Surface albedo varies according to the material
  - Spatially

TABLE 2.3 Typical Albedo of Various Surfaces

SURFACE	ALBEDO (PERCENT)
Fresh snow	75 to 95
Clouds (thick)	60 to 90
Clouds (thin)	30 to 50
Venus	78
Ice	30 to 40
Sand	15 to 45
Earth and atmosphere	30
Mars	17
Grassy field	10 to 30
Dry, plowed field	5 to 20
Water	10*
Forest	3 to 10
Moon	7

*Daily average.

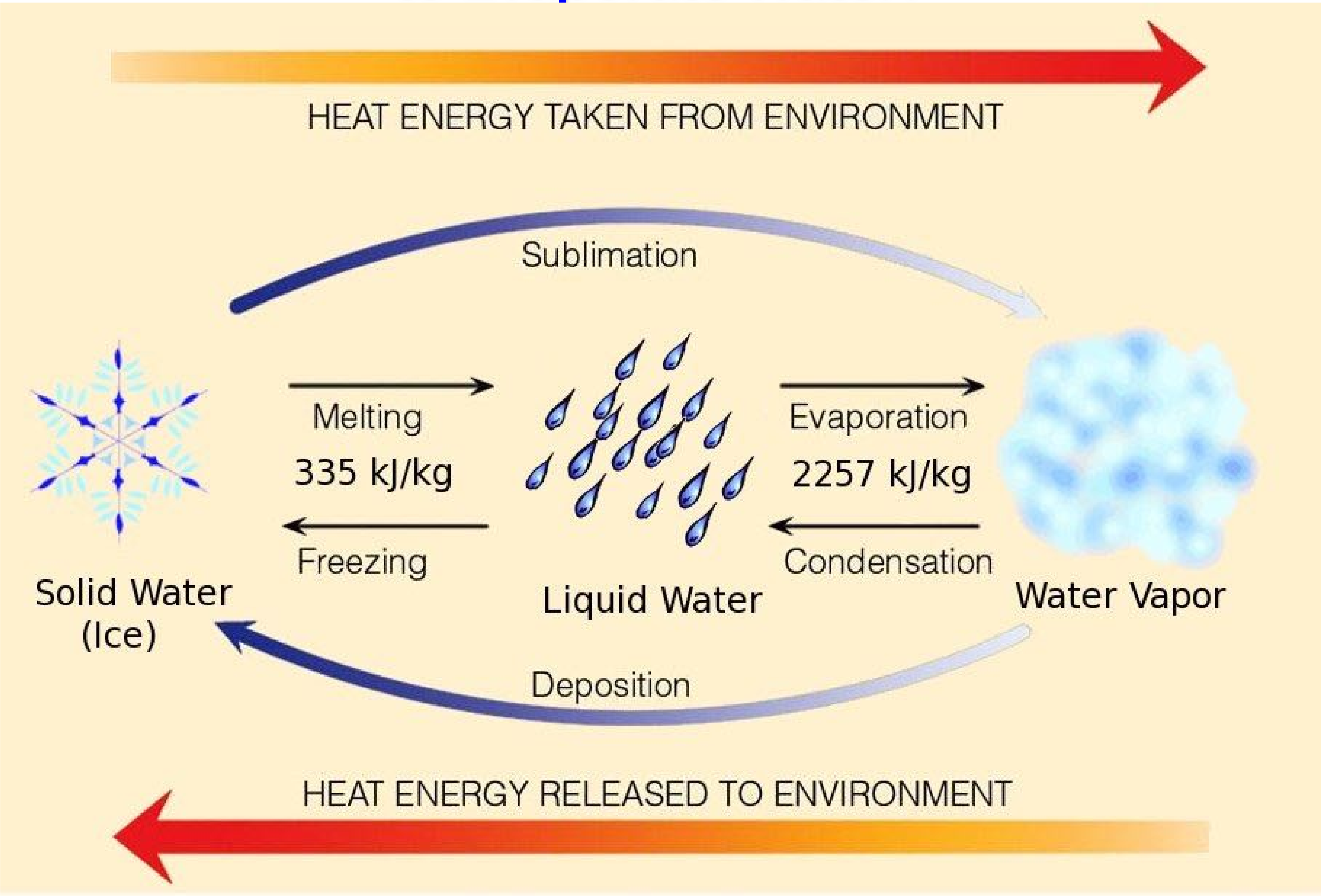
Heat Transfer



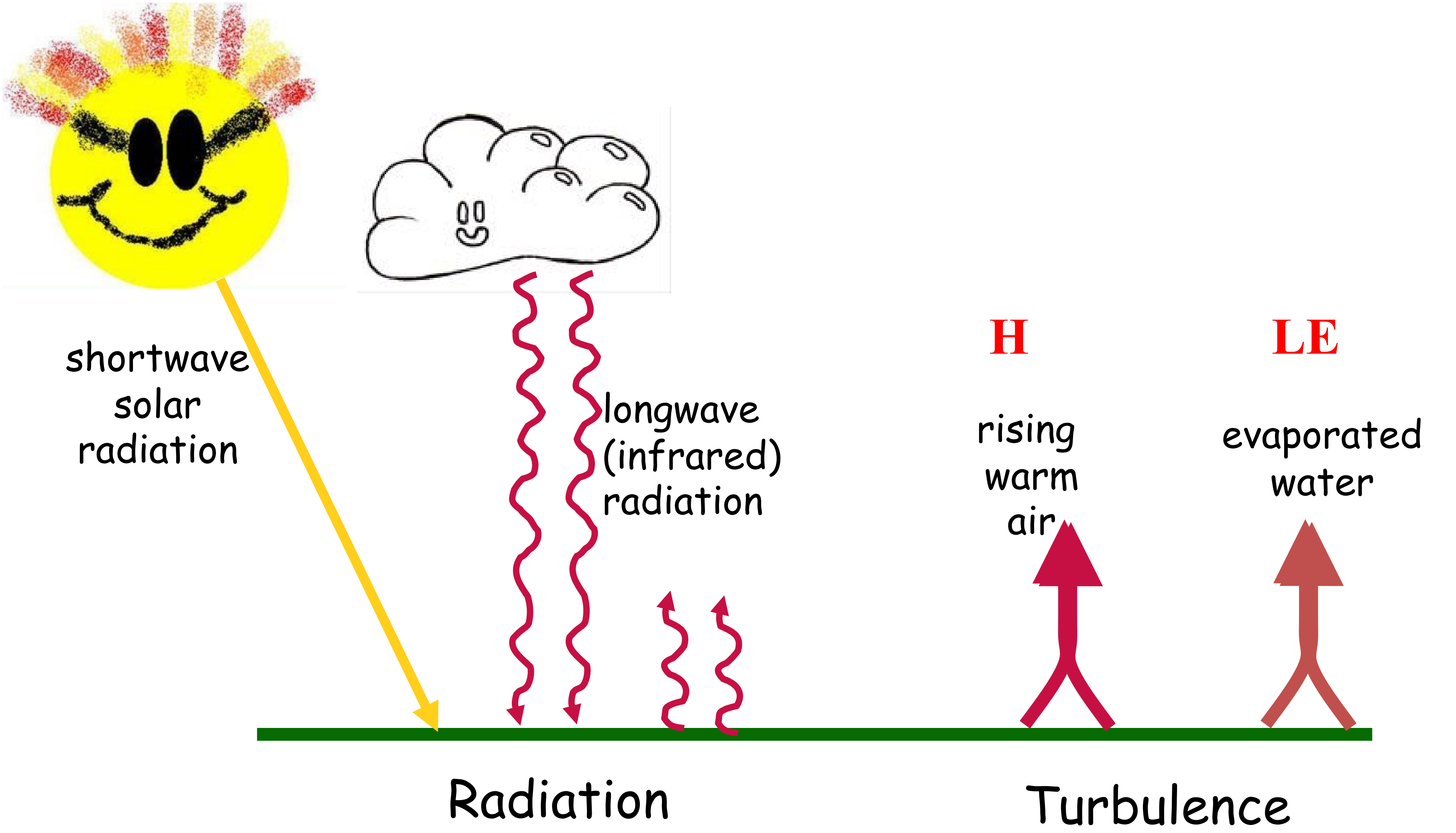
Conduction is by hot molecules colliding with neighbors
Convection is by hot stuff moving in bulk from place to place

It Takes a Lot of Energy

to Evaporate Water!

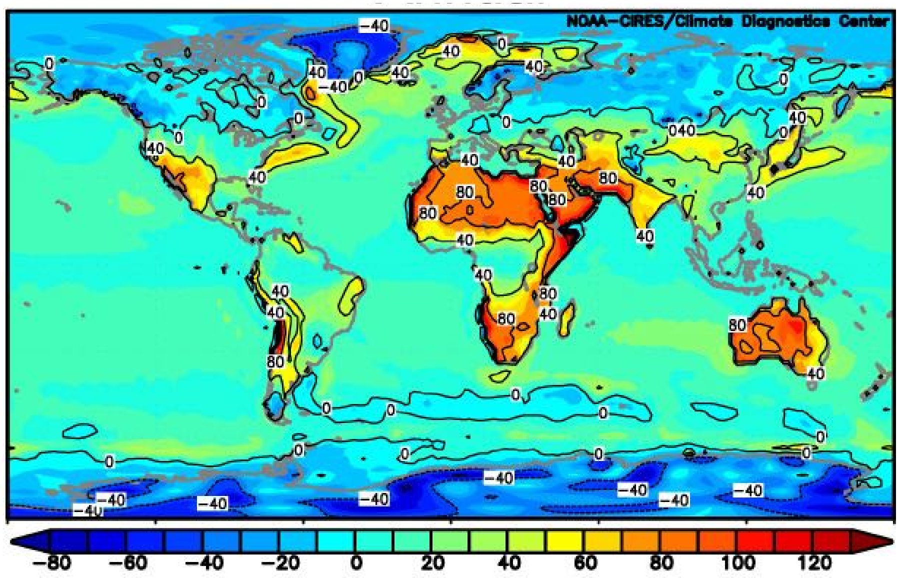


Energy Balance of Earth's Surface

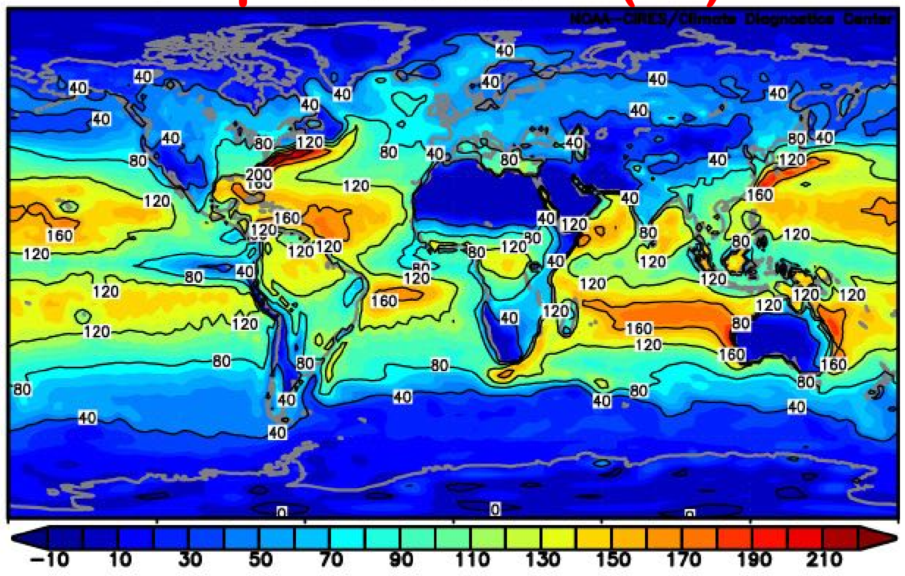


Energy from the Surface to the Air

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