How Climate Works

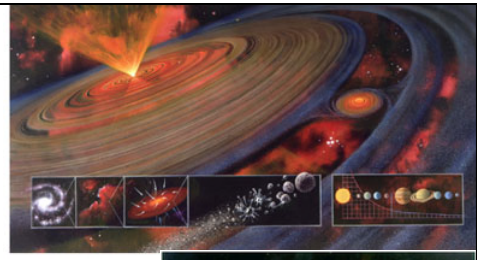
Please skim through Chapters 1 – 6 in Bonan Textbook

The Earth System

The Earth's climate results from the interaction of many properties and processes

- Solar radiation and orbital geometry
- The size, gravitational force, and rotation rate of the planet
- The composition, structure, and internal dynamics of the planet
- The geography of continents, glaciers, mountain ranges, and oceans
- Ocean properties and circulation
- Atmospheric constituents, their chemical interactions, circulation, and the hydrologic cycle
- The living ecosystems that inhabit the planet, and the biogeochemical transformations they conduct

Origins



- Earth formed by gravitational accretion ~ 4.7 billion years ago
- Solar "constant" was ~ 30% less than today
- Impact heating kept surface hot and sterile
- Giant collision separated the Moon and helped differentiate chemical layers

Cross-Section of Our Dynamic Planet!

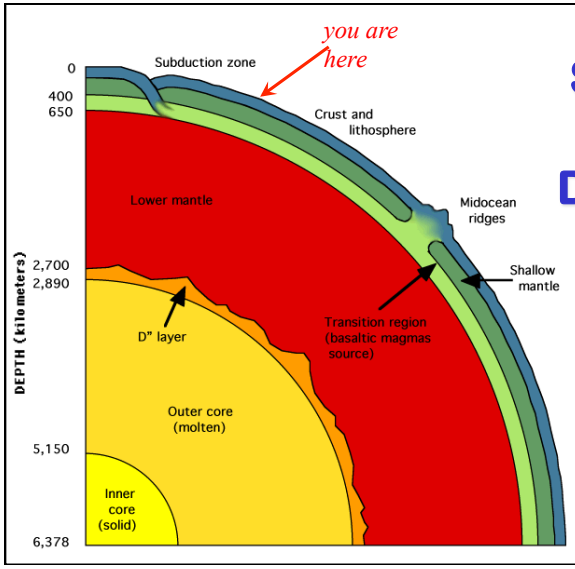
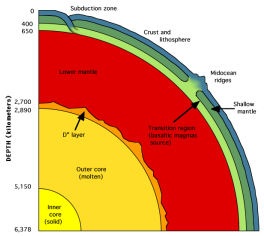
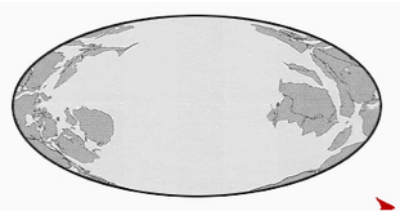


Plate Tectonics and Climate

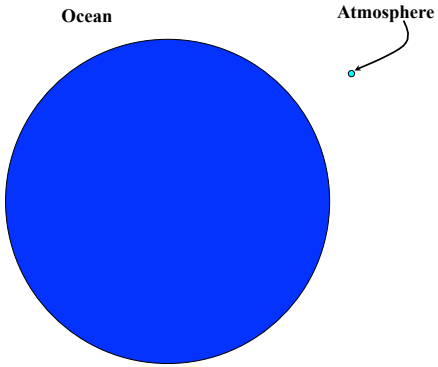
- Continental plates are lighter (buoyant) and rise in collisions, whereas oceanic plates subduct
- Continents can "bunch up" due to collisions, forming *supercontinents* ("Pangea," "Gondwana")



- Rearrangement of ocean basins dramatically changes poleward heat transport



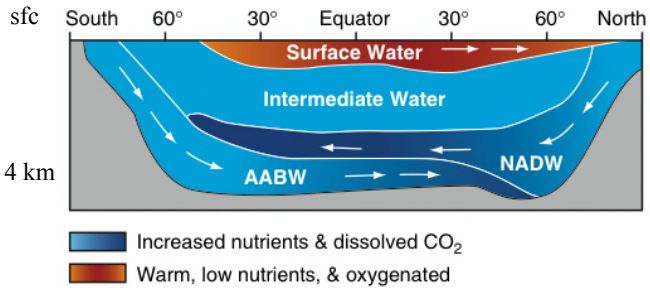
Energy Reservoirs



- The oceans are about 4000 m deep
- The top 10 m equal the mass of the atmosphere
- The top 3 m equal the heat capacity of the atmosphere!

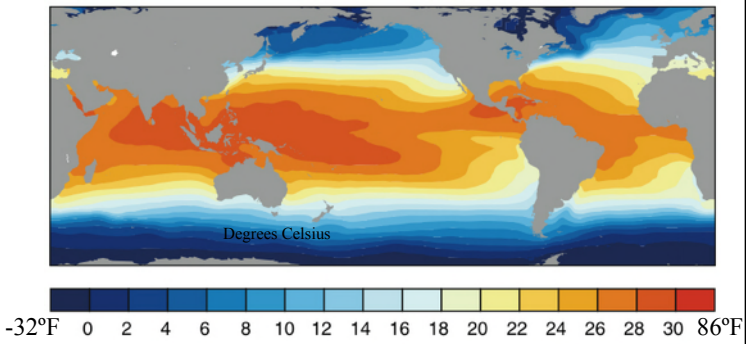
The state of the oceans determines the climate on time scales of thousands to millions of years!

Vertical Structure of the Oceans



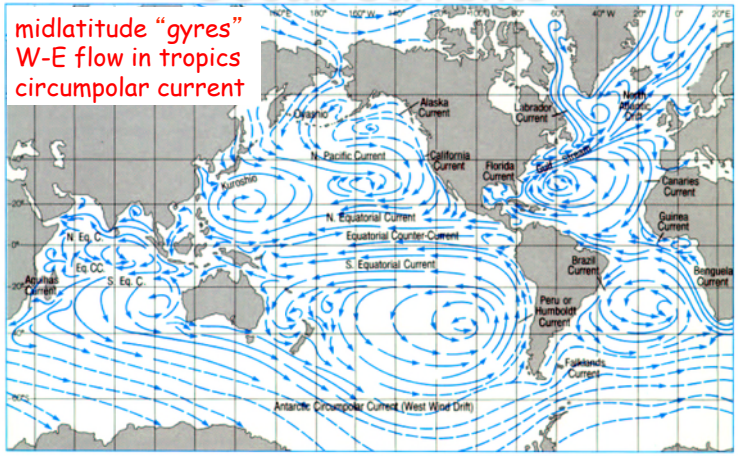
- Warm buoyant "raft" floats at surface
- Cold deep water is only "formed" at high latitudes
- Very stable, hard to mix, takes ~ 1000 years!
- Icy cold, inky black, most of the ocean doesn't know we're here yet!

Sea-Surface Temperatures



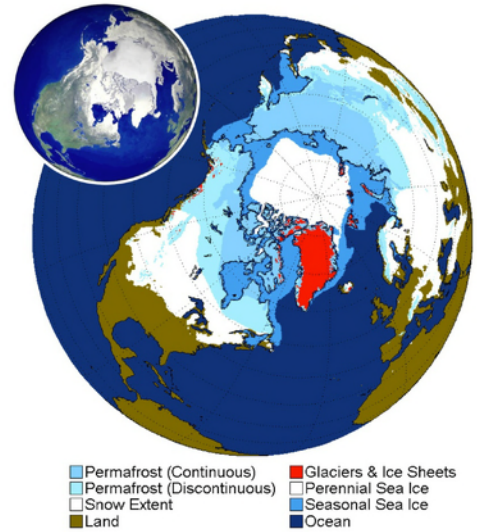
- W. Pacific "Warm Pool"
- Effects of Western vs Eastern boundary currents!

Ocean Currents



How are these known? Effects on poleward energy transport?

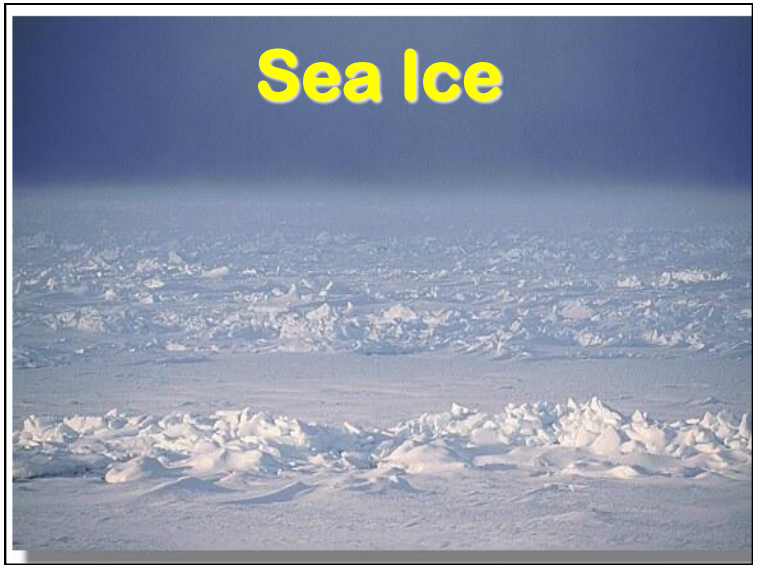
Ice and Snow



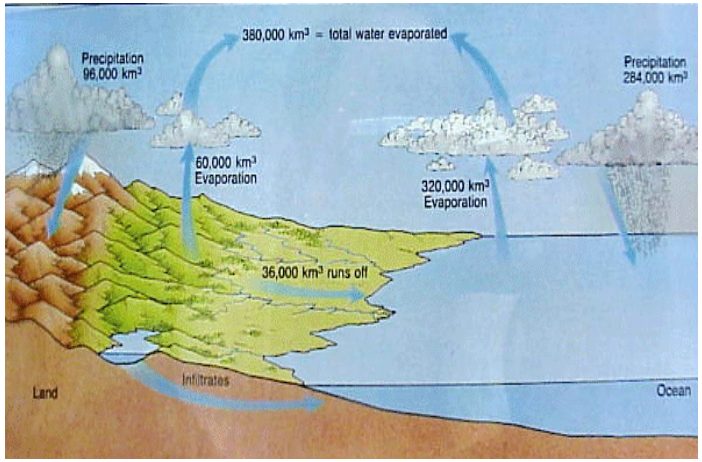
Land and Sea Ice

- Greenland is covered with ice to depths of several kilometers
- Permanent ice cover further north overlies an isolated ocean basin

Sea Ice



The Earth's Hydrologic Cycle



Clouds of Many Kinds

Energy and Radiation

Heat Transfer

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

Electromagnetic Radiation

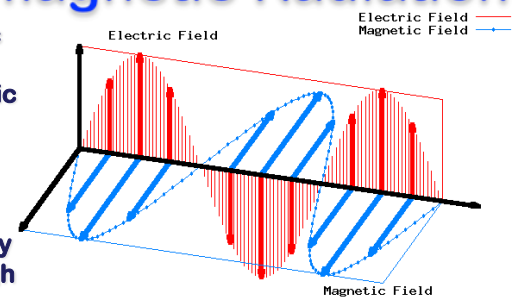
Changing electric fields create changing magnetic fields …

and vice versa!

This makes energy move even through empty space

We can see it, feel it

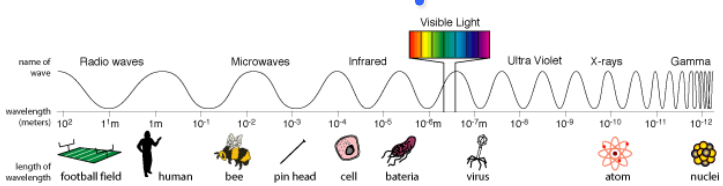
Plants harvest it directly, and we harvest them!



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

Distance it goes in one cycle is called the wavelength

Electromagnetic Radiation Spectrum



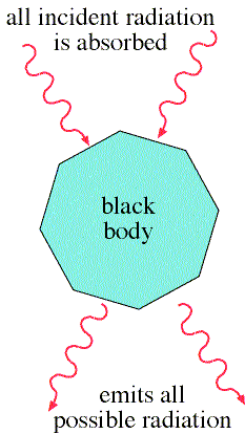
Shorter waves carry more energy than longer waves

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

Thermal Radiation

"Everything emits heat"

"Black Body"

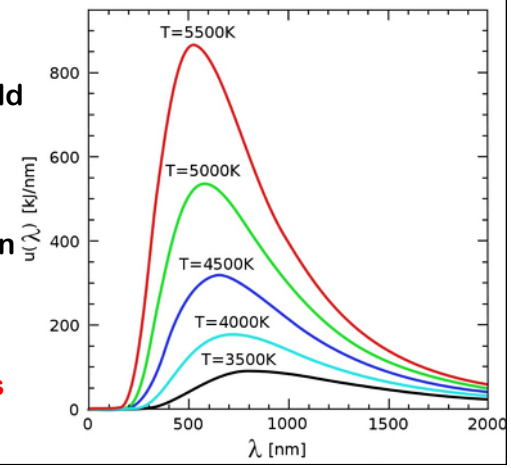


Just an idea, really …

- Idealized object that absorbs all radiation that falls on it
- No transmission, no reflection, just absorption and emission
- Emits energy according to temperature

Blackbody Emission

- Hot objects emit *much* more than cold objects at every wavelength
- Peak emission at shorter waves at higher temperatures



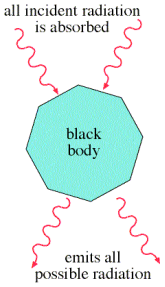
Energy and Power

- Energy is an intrinsic property of an object, measured in Joules
- Power is a rate of transfer of energy, or a flow of energy, measured in Joules per second
- We define:
  1 Joule per second = 1 Watt

Blackbody Power

$$F_{BB} = \sigma T^4$$

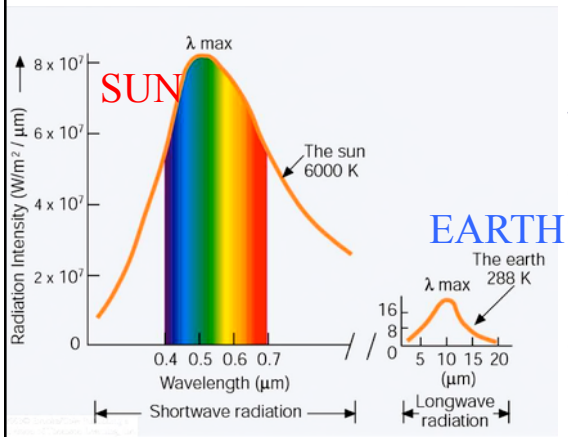
Stefan-Boltzmann Law



- Total rate of energy emission by a blackbody is proportional to its $T \times T \times T \times T = T^4$
- Proportionality constant σ is measured to be the same for all blackbodies

$\sigma = 5.67 \times 10^{-8}$ is the *Stefan-Boltzmann constant*

Thermal Emission

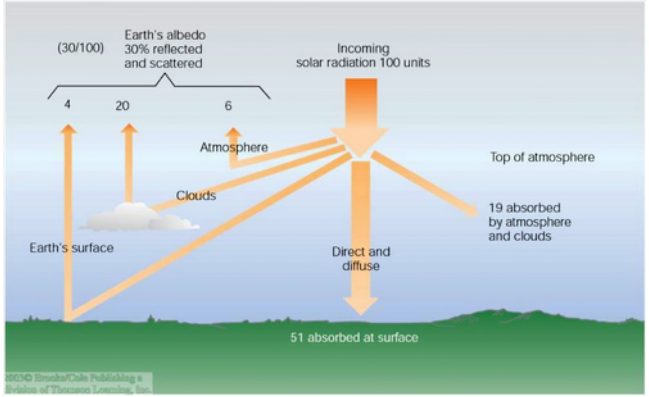


Both are almost perfect blackbodies!

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

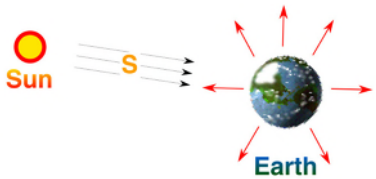
Solar Radiation



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

Planetary Energy Budget

Energy Balance

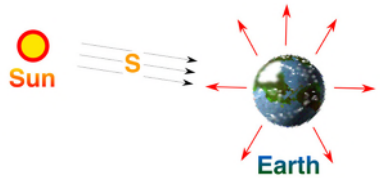


$F_{in} = F_{out}$

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



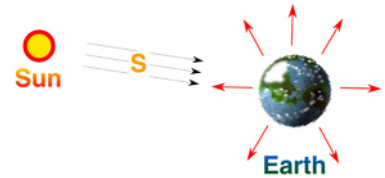
$F_{in} = F_{out}$

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

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

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

Energy Balance



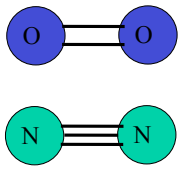
$F_{in} = F_{out}$

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

But the observed surface temperature is about 288 K

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

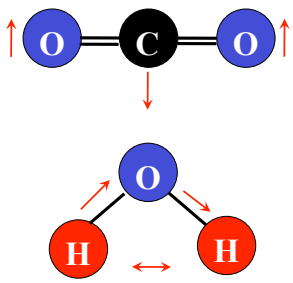


Diatomic molecules can vibrate back and forth like balls on a spring, but the ends are identical

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"

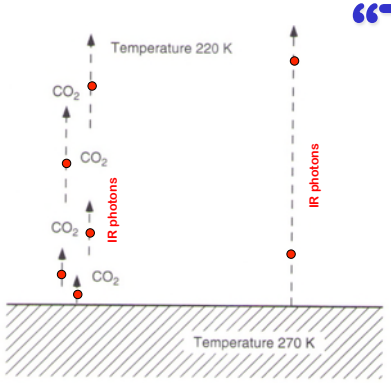
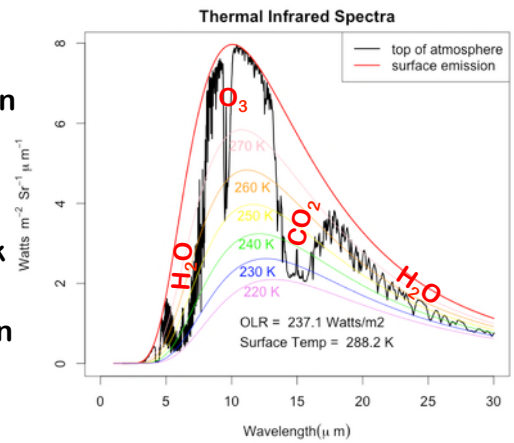


Figure 4-4 A comparison of the fate of infrared light in the optically thick CO_2 bend frequency (*left*) versus the optically thin atmospheric window (*right*).

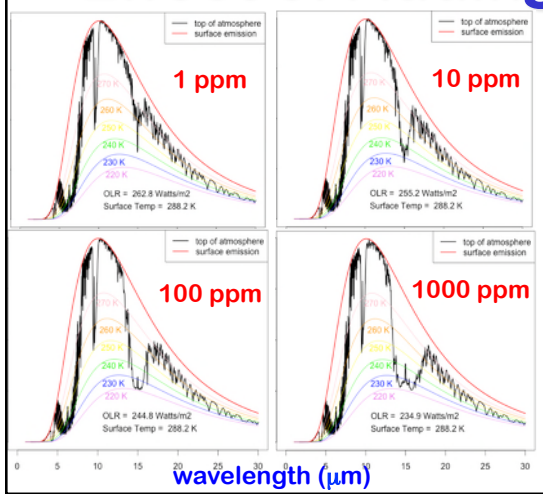
- In CO_2 absorption bands, atmosphere is totally opaque to IR photons
- They get absorbed and re-emitted higher up
- It's cold up there!
- Think about the Layer Model

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

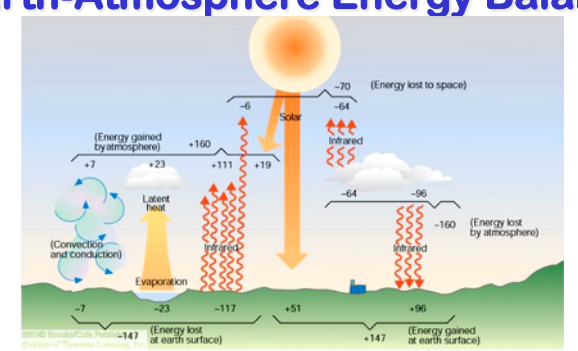


Effect of Adding CO_2



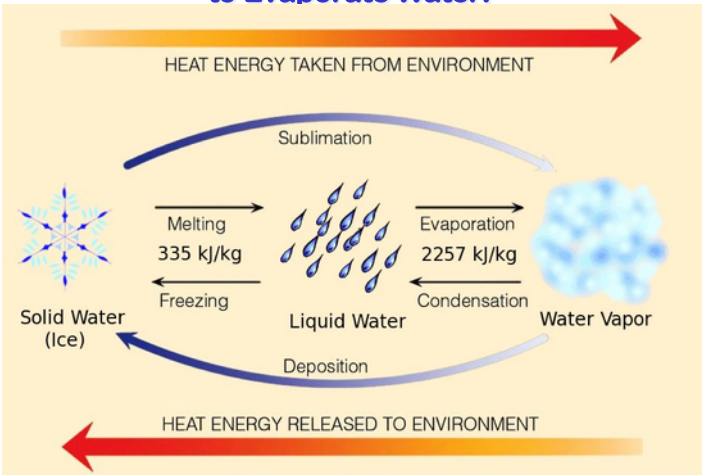
- Optically thick regions are as cold as they can get
- But the thick regions get wider with added CO_2
- Rate of total emission (area under black curve) decreases less and less

Earth-Atmosphere Energy Balance

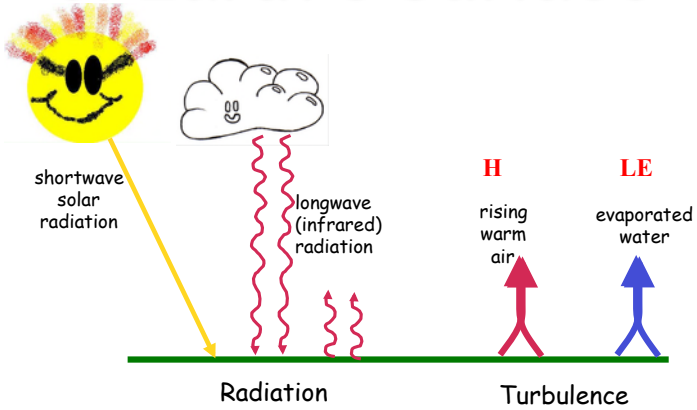


Earth's surface absorbs the 51 units of shortwave and 96 more of longwave energy units from atmospheric gases and clouds.
These 147 units gained by earth are due to shortwave and longwave greenhouse gas absorption and emittance.
Earth's surface loses these 147 units through convection, evaporation, and radiation.

It Takes a Lot of Energy
to Evaporate Water!

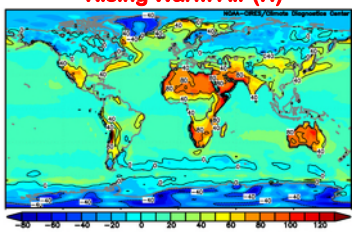


Energy Balance of Earth's Surface

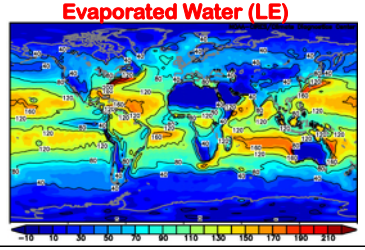


Energy from the Surface to the Air

Rising Warm Air (H)

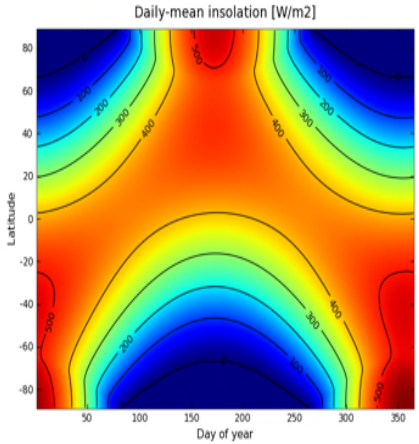


Evaporated Water (LE)



- 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

Daily Solar at Top of Atmosphere



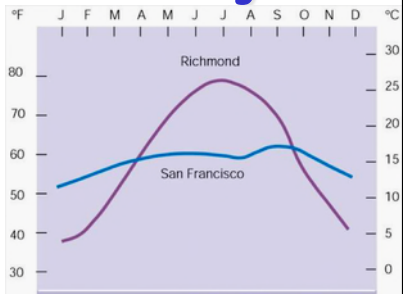
- 75° N in June gets more sun than the Equator!
- Compare N-S changes by seasons
- Very little tropical seasonality

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

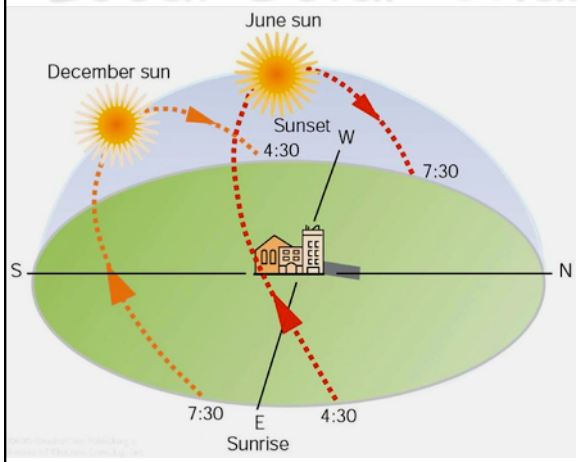
San Francisco is downwind of the Pacific Ocean

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

Landscape Solar Response

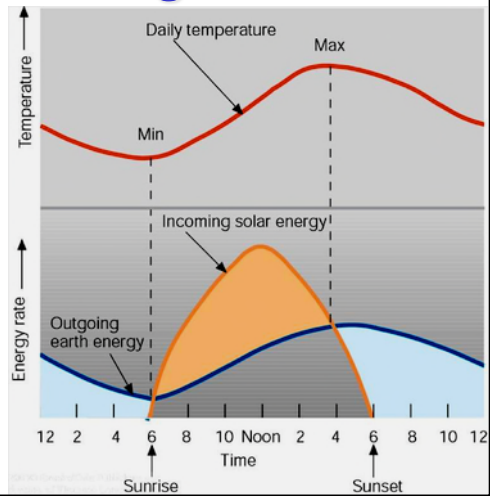
South facing slopes receive greater insolation, providing energy to melt snow sooner and evaporate more soil moisture.

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

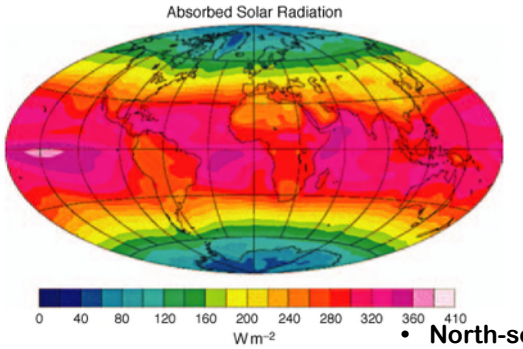
Temperature Lags Radiation

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.



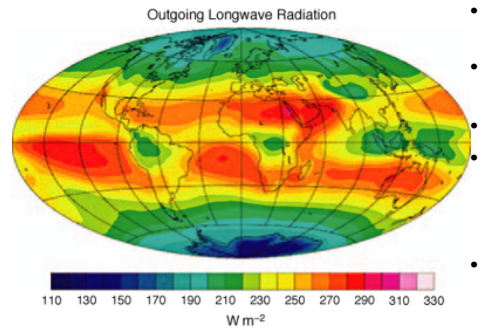
Energy In



Annual Mean

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

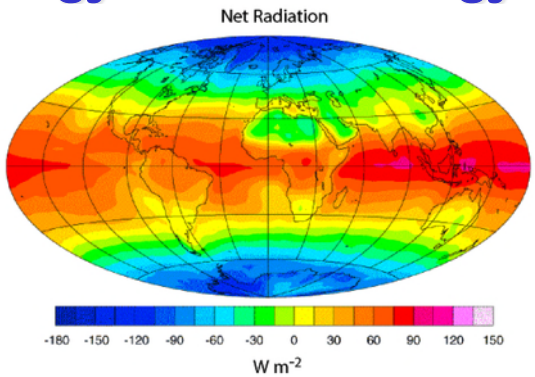
Energy Out



Annual Mean

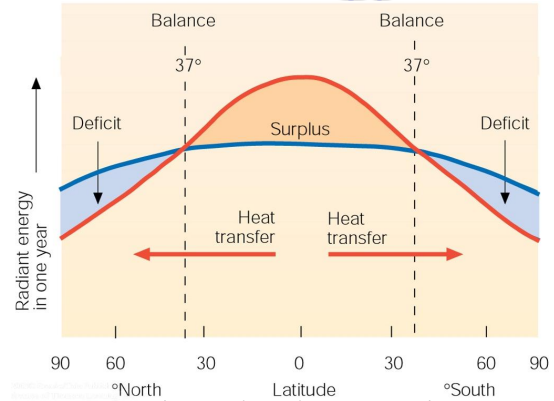
- Given by $\varepsilon\sigma T^4$ (which T?)
- Combined surface and atmosphere effects
- Decreases with latitude
- Maxima over subtropical highs (clear air neither absorbs or emits much)
- Minima over tropical continents (cold high clouds)
- Very strong maxima over deserts (hot surface, clear atmosphere)

Energy In minus Energy Out



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

Earth's Energy Balance

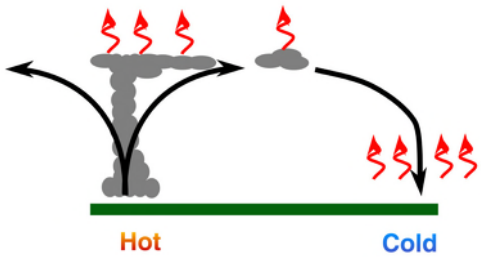


- Must be balanced by horizontal transport of energy by atmosphere and oceans!

Atmospheric Circulation

The Job of the Atmosphere

is to let the energy out!

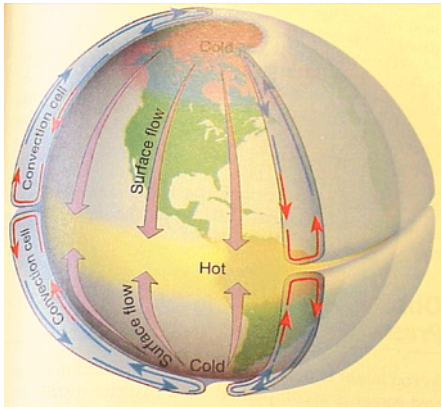


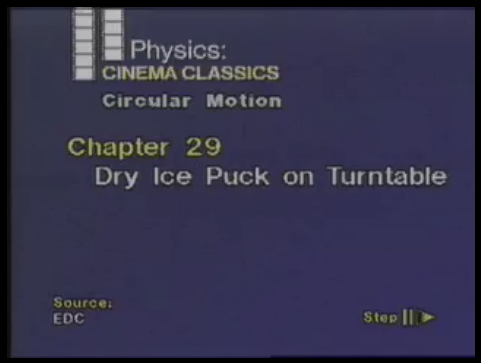
"Piles up" in tropics "Escapes" near poles and aloft

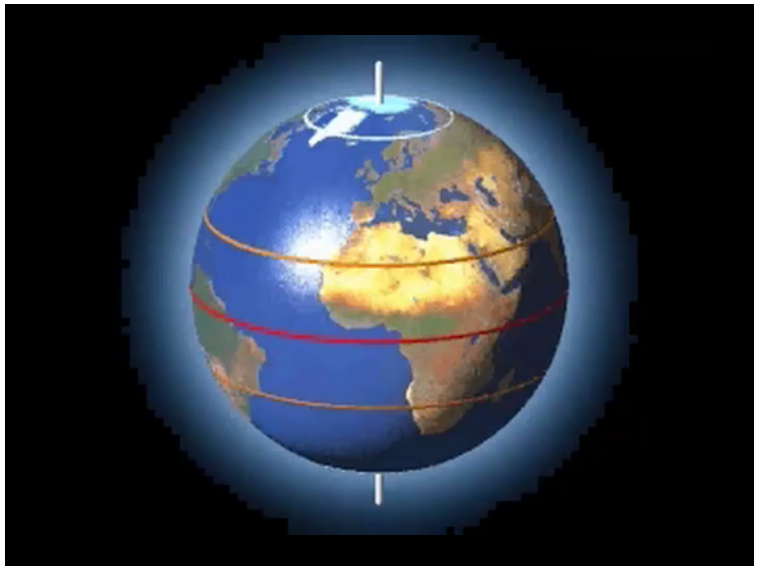
The movement of the air (and oceans) allows energy to be transported to its "escape zones!"

If the Earth Didn't Spin …

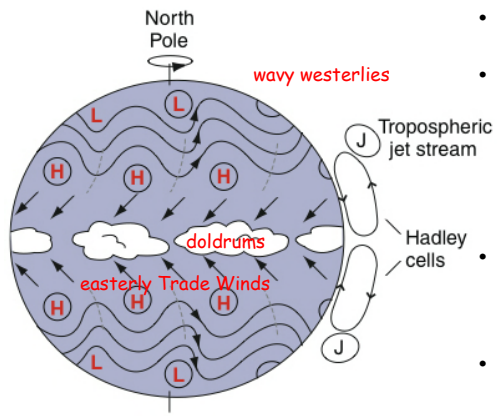
- Warm air rises (tropics)
- Cold air sinks (poles)
- Energy transported from equator toward poles







Winds on the Rotating Earth

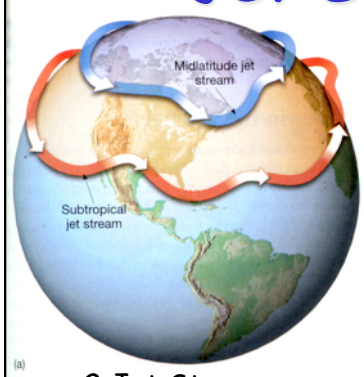


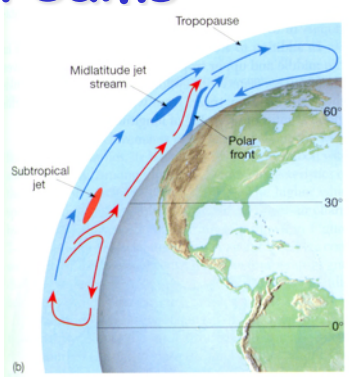
- Deep convective cells confined to tropics
- Condensation heating in rising branch of Hadley Cell lifts the center of mass of the atmosphere (converts latent to potential energy)
- Downhill slope toward winter pole produces jet streams in middle latitudes
- Jet is unstable to small perturbations, breaks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

Global Circulation

- **Hadley cell** (thermally direct cell)
  - driven by *N-S gradient in heating*
  - air *rises near equator and descends* near 30 degrees
  - explains deserts; trade winds; doldrums
- **Ferrel Cell** (indirect thermal cell)
  - driven by heat transports of *eddies*
  - air *rises near 60 degrees* and descends near 30 degrees
  - explains surface westerlies from 30-60
- Weak winds found near
  - Equator (doldrums)
  - 30 degrees (horse latitudes)
- Boundary between cold polar air and mid-latitude warmer air is the *polar front*

Jet Streams





- 2 Jet Streams
  - Midlatitude Jet gives us storms
  - Subtropical Jet weaker, higher up

Polar Vortex

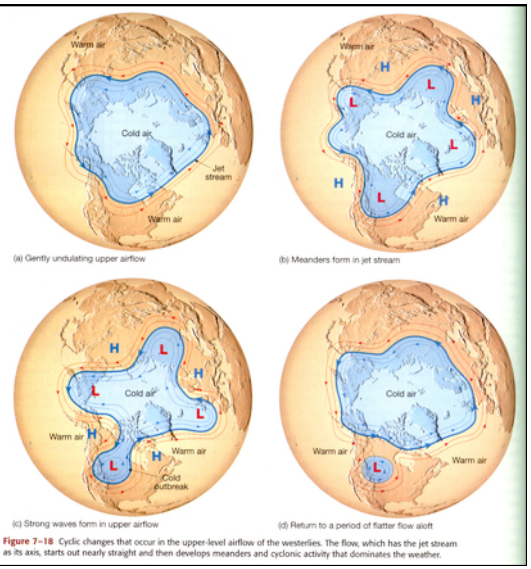


Figure 7–18 Cyclic changes that occur in the upper-level airflow of the westerlies. The flow, which has the jet stream as its axis, starts out nearly straight and then develops meanders and cyclonic activity that dominates the weather.

Atmospheric Circulation in a nutshell

- Hot air rises (rains a lot) in the tropics
- Air cools and sinks in the subtropics (deserts)
- Poleward-flow is deflected by the Coriolis force into westerly jet streams in the temperate zone
- Jet streams are unstable to small perturbations, leading to huge eddies (storms and fronts) that finish the job

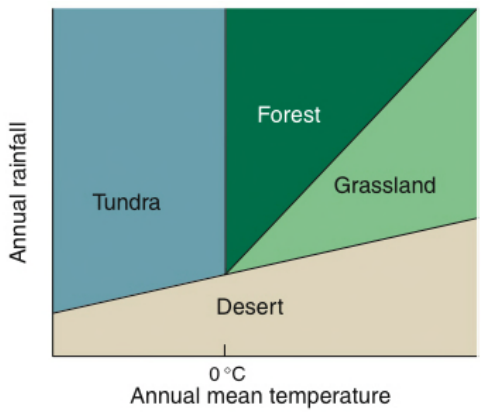
Climates of the World

- **Deep Tropics**: hot and wet, with little seasonal variation
- **Seasonal tropics**: hot, with "summer" rain and "winter" dry (monsoon)
- **Subtropics**: dry and sunny, deserts and savannas, often with a well-defined rainy season (summer *or* winter)
- **Midlatitude temperate zone**: warm summers, cold winters, moisture varies by location but often comes in episodes throughout the year
- **Polar regions**: very cold, generally very dry, dark all winter!

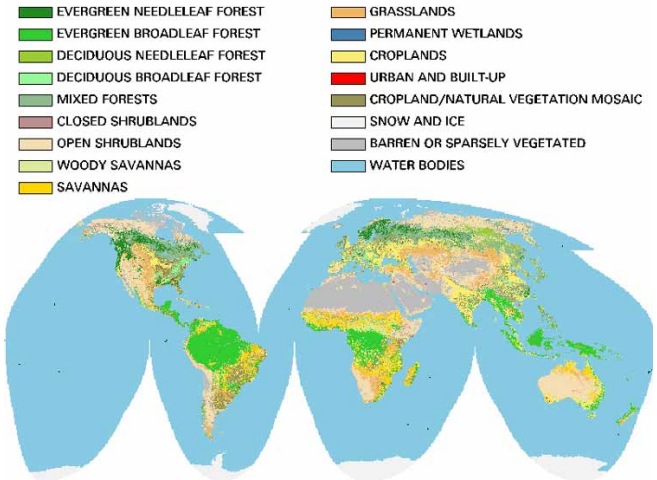
Weather vs Climate

- **Weather:**
  the state of the atmosphere at a place and time as regards heat, cloudiness, dryness, sunshine, wind, rain, etc.
- **Climate:**
  the weather conditions prevailing in an area in general or over a long period of time

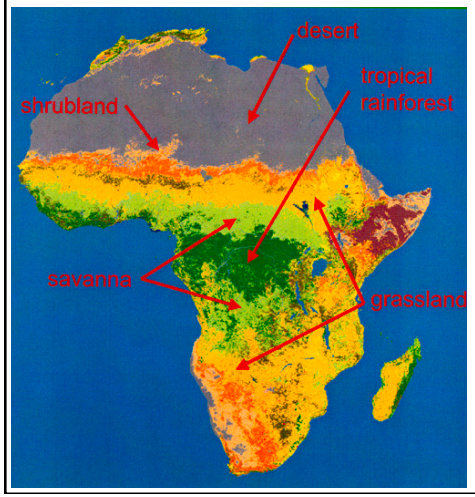
Climate and Vegetation



Land Vegetation



Tropics and Subtropics



- Rainfall and its seasonal distribution determine the distribution of plant types
- Savannas and grasslands are adapted to seasonal and longer dry periods
- Landscape patterns strongly influence radiation budgets and climate

Tropical Forest

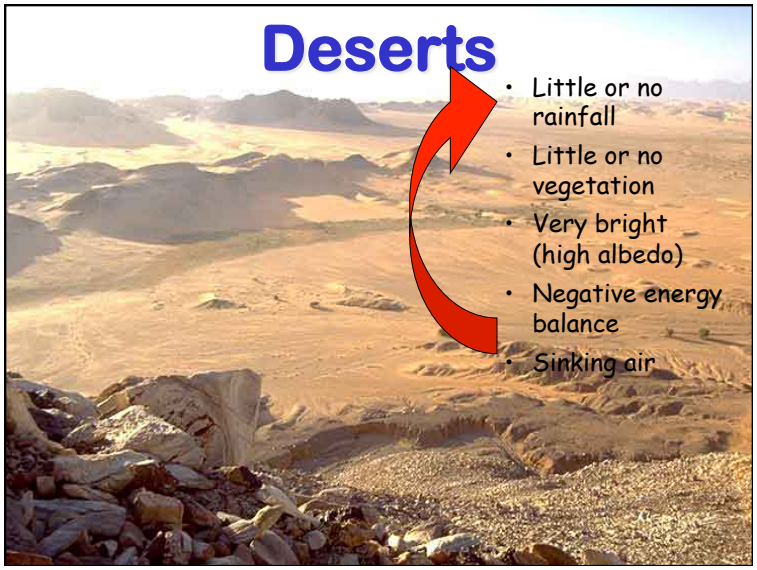
Located in equatorial zone of mean rising motion and heavy precipitation during much of the year

Dark color ("albedo"), very strong energy absorption

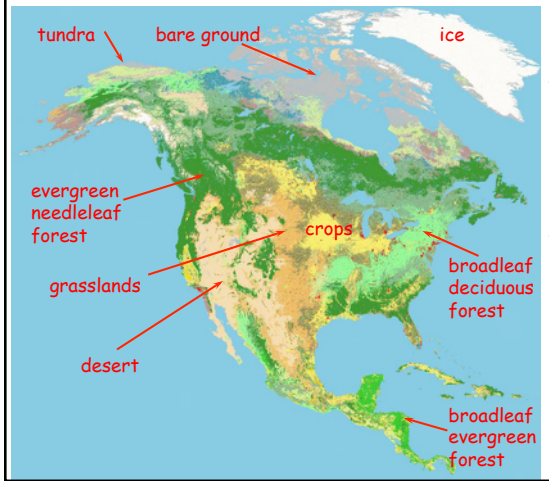
Broadleaf evergreen trees with extensive understory, as many as 300 tree species per km^2

The most productive ecosystems on Earth

Some are very deeply rooted (> 10 m) and can withstand periods of severe drought

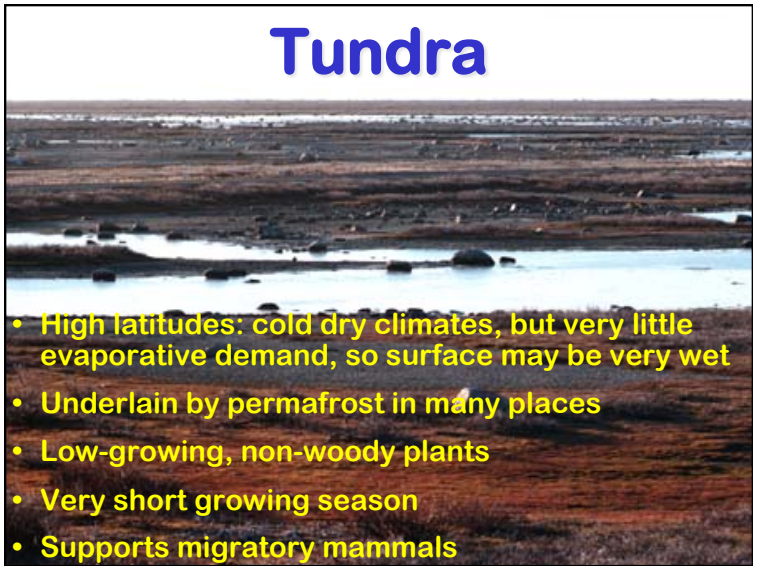


Temperate and Boreal Zones



- Latitude and continentality are both very important
- Moisture, growing season, and human land use also play roles


Boreal Forest
Mostly evergreen, needleleaf trees with little understory
Short growing season, susceptible to drought and fire
Low evaporative demand, so surface may be wet (bogs and fens)
Very low albedo


Tundra
• High latitudes: cold dry climates, but very little evaporative demand, so surface may be very wet
• Underlain by permafrost in many places
• Low-growing, non-woody plants
• Very short growing season
• Supports migratory mammals