Follow the Energy

an overview of the Earth system

What is energy?

Conservation of Energy

Energy flows downhill from hot to cold

Earth's energy budget

The "job" of the atmosphere & oceans

A brief tour of the Earth system

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 of energy is absolutely central to understanding the physical world, yet is very hard to define precisely

"Energy Changes Make Things Happen"

Dave Watson, http://www.ftexploring.com

- Energy is a property or characteristic of matter that makes things happen, or, in the case of stored or potential energy, has the "potential" to make things happen.
- Without energy, nothing would ever change, nothing would ever happen. You might say energy is the ultimate agent of change, the mother of all change agents.

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"The Mysterious Everything"

Whatever happens is caused by it. …

You need it to run, to walk, to sit, to think,
to sleep, "perchance to dream"…

You can't get mad without it.
You can't get glad without it.
You can't get anything without it.

It makes the wind blow, rain fall,
and lightning zap and thunder.

It "feeds" volcanoes and earthquakes.

It drives tidal waves, typhoons, and tornadoes.

It powers the universe.

It powers bacteria.

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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

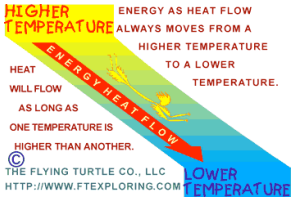
- Radiant Energy -- light
- Kinetic Energy -- motion
- Gravitational Potential Energy -- height
- "Internal Energy"
  - Temperature, Pressure -- hot air
  - Chemical energy
  - Nuclear energy

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

If Energy is Conserved …

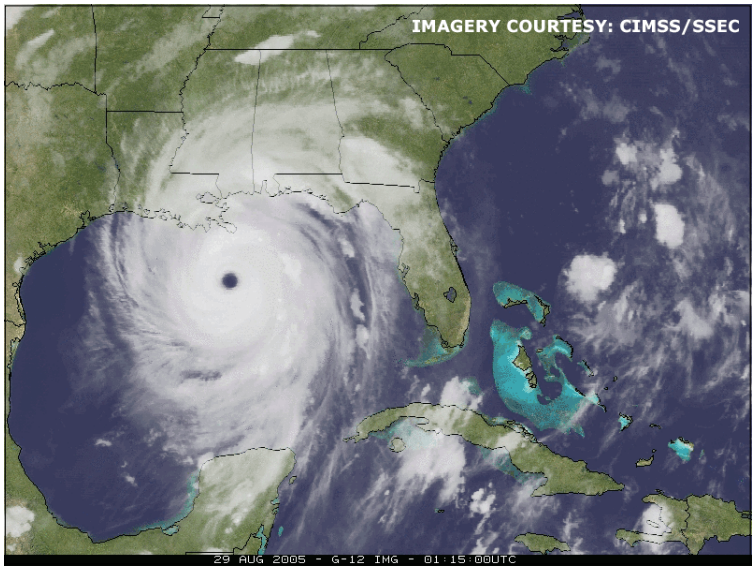
then why do we need to "conserve energy?"

- 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)

Hurricane Andrew Devastation in Homestead, Florida
August 24, 1992



It all starts with the Sun

- Nuclear fusion in the Sun powers all changes on the Earth!
- Solar energy heats the air, lifts it, blows it around, evaporates water, makes snowstorms
- Conversion of solar energy and downhill dissipation as heat energy drive all weather and climate phenomena
- Energy comes in hot, and goes out cold, at 342 W m^{-2}

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

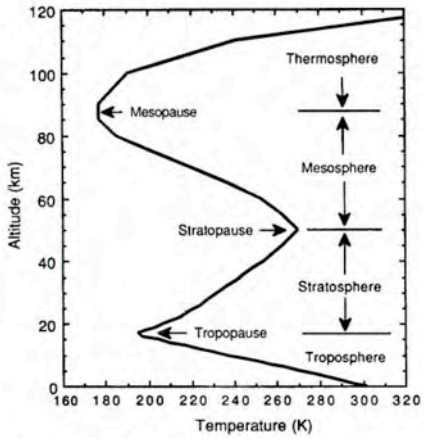
What's Missing
from the 0-D energy balance model?

- 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

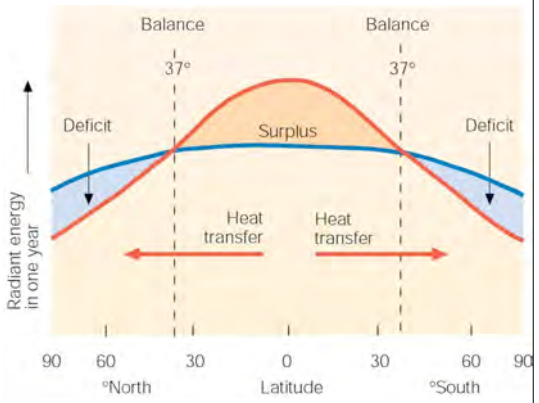
Vertical Thermal Structure



- Heated from below by latent and sensible heat fluxes
- Heated in stratosphere by ozone absorption

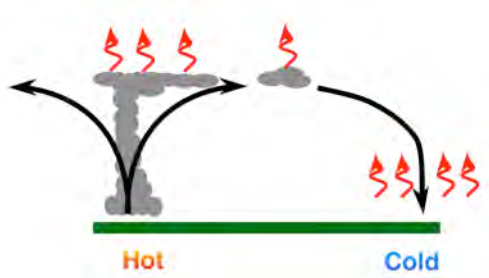
Earth's Energy Balance

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



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!"

Why Does the Wind Blow?

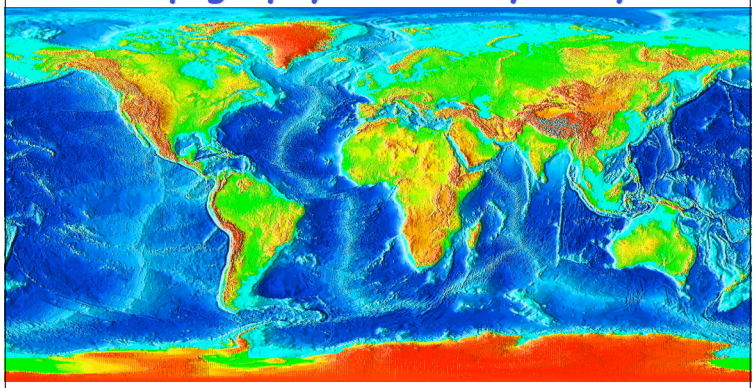
- Solar heating is greater than longwave cooling in the tropics: energy accumulates there, both in the atmosphere and the oceans
- Longwave cooling is greater than solar heating near the poles: energy is lost there, by thermal radiation to outer space
- The "job" of the atmosphere and the oceans is to transport energy from where it accumulates to where it can be lost (poleward and upward)
- This job is difficult because of the Coriolis force

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
- Atmospheric constituents, circulation, and the hydrologic cycle
- Ocean properties and circulation
- Land surface hydrology, biology, and geochemistry
- The geography of continents, glaciers, mountain ranges, and oceans

Topography and Bathymetry



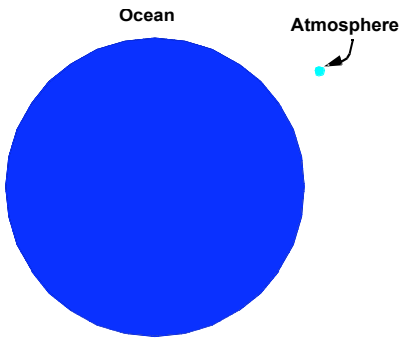
- What controls these variations?
- What are the consequences in the atmosphere?
- What are the consequences in the oceans?

Water on Earth

Water reservoir	Depth if spread over the entire surface of Earth (m)	Percent of total
Oceans	2650	97
Icecaps and glaciers	60	2.2
Groundwater[a]	20	0.7
Lakes and streams[a]	0.35	0.013
Soil moisture[a]	0.12	0.013
Atmosphere	0.025	0.0009
Total	2730	100

- Atmosphere is a bit player in storage of water
- Very dynamic cycling

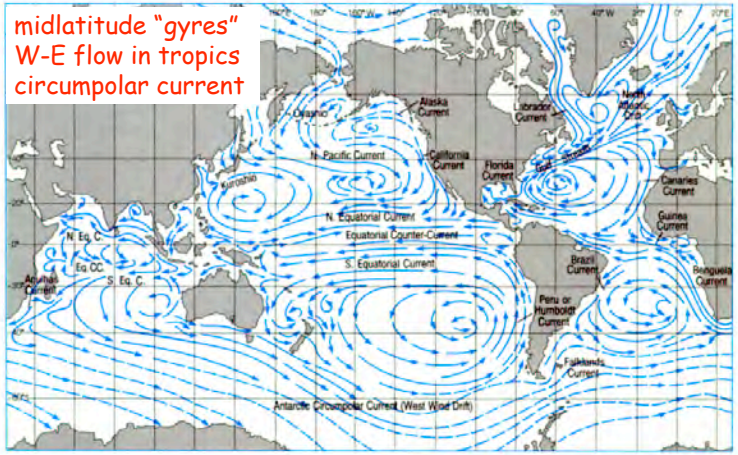
Energy Reservoirs



- 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!

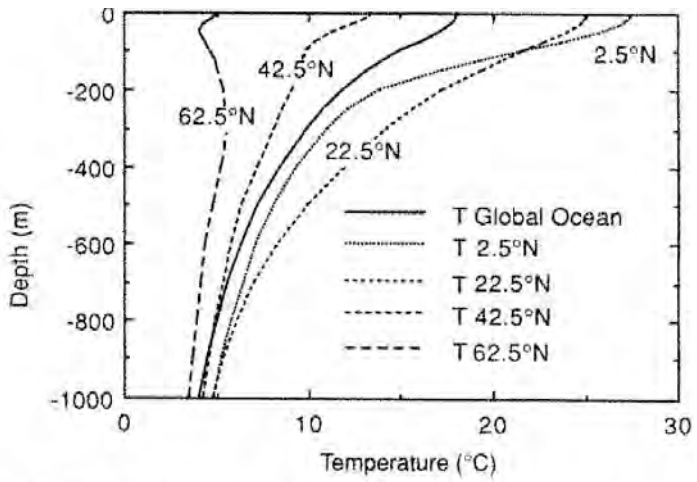
The state of the oceans determines the climate on time scales of thousands to millions of years!

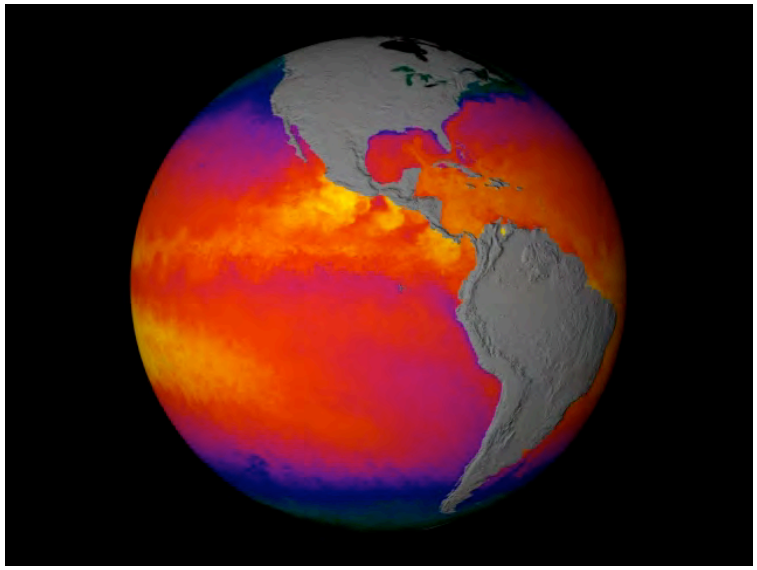
Ocean Currents



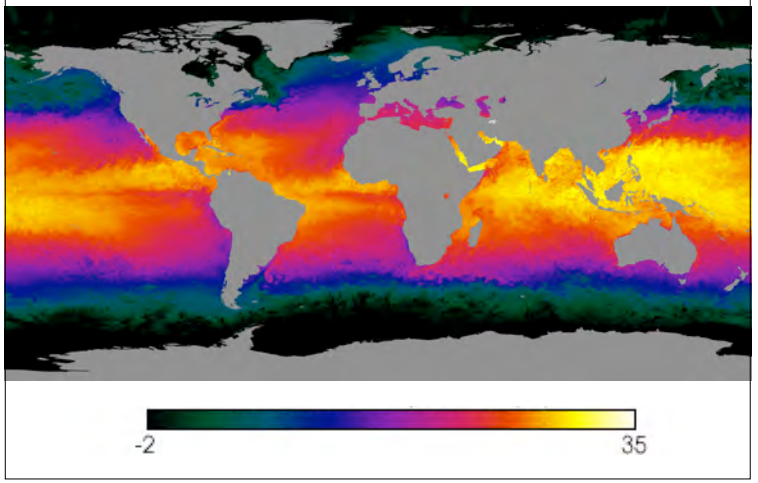
How are these known? Effects on poleward energy transport?

Ocean Temperatures





Sea Surface Temperature

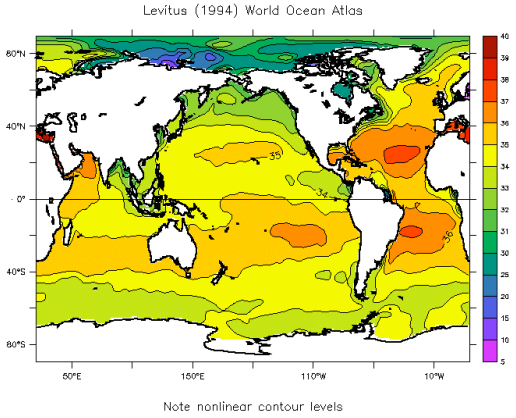


Dissolved constituents in seawater

Component	Grams per kilogram
Chloride	19.353
Sodium	10.76
Sulfate	2.712
Magnesium	1.294
Calcium	0.413
Potassium	0.387
Bicarbonate	0.142
Bromide	0.067
Strontium	0.008
Boron	0.004
Fluoride	0.001

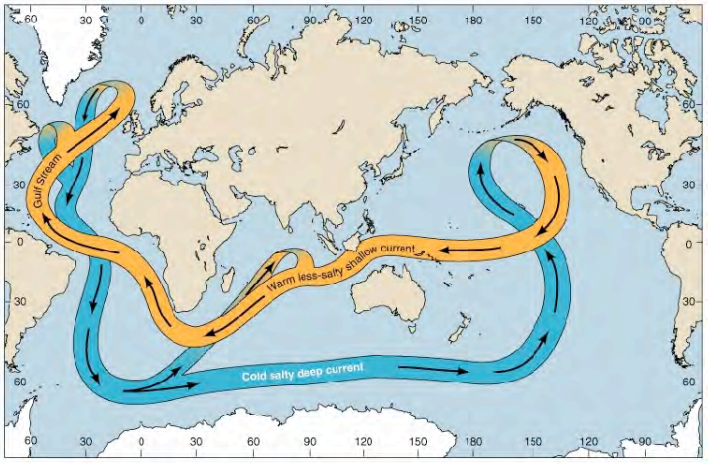
- Same composition in all seawater
- Where does this stuff come from?

Sea Surface Salinity



- Freshest water at highest latitudes
- Saltiest water in subtropics (especially in Atlantic)
- Why?

Thermohaline Circulation



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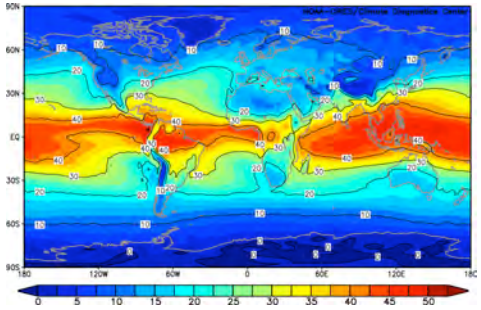
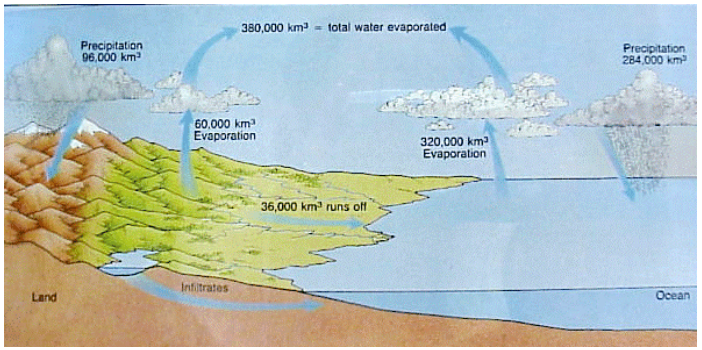
Atmospheric Water

annual mean total water vapor (mm)

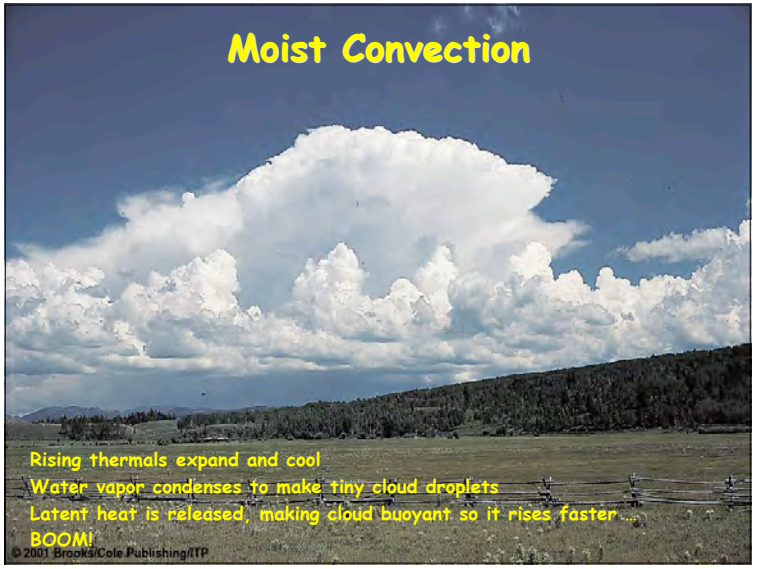


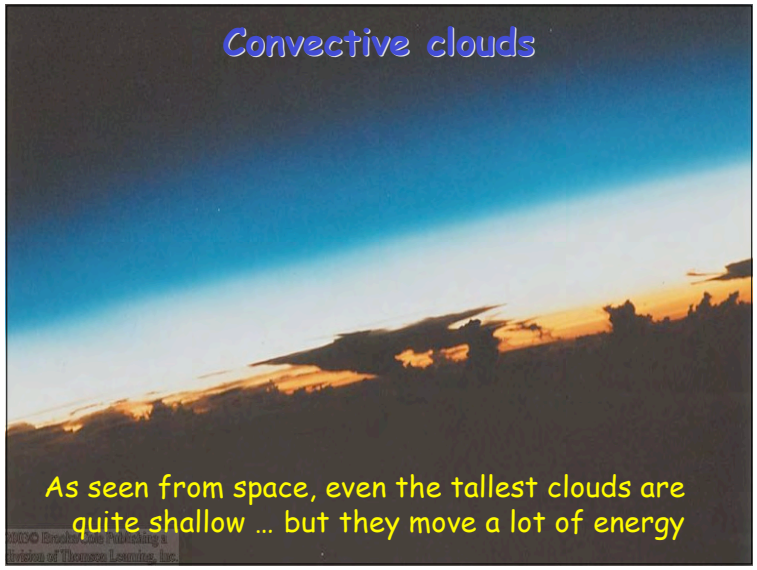
- Way more water vapor over tropics
- Follows surface temperature
- Mean ~ 25 mm (1 inch)
- Mean precip rate is about 2.6 mm/day
- Residence time ~ 9 days

The Earth's Hydrologic Cycle



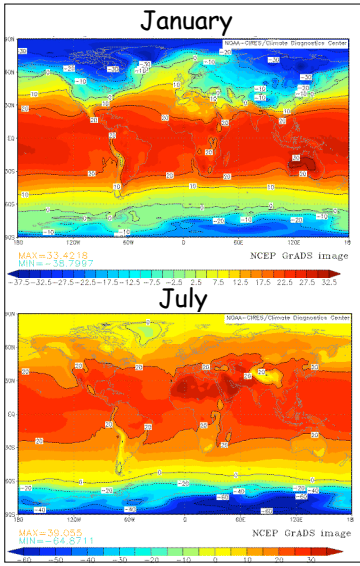
Moist Convection



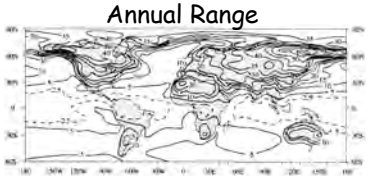


Atmospheric Circulation
in a nutshell

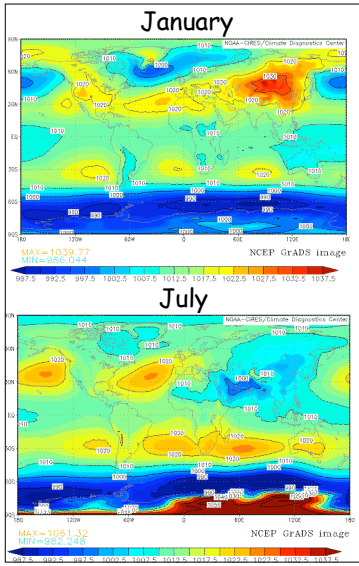
- Hot air rises (it rains a lot) in the tropics
- Air cools and sinks in the subtropics (deserts)
- Poleward-flow is deflected by the Coriolis force into westerly jet streams in the temperate zone
- Jet streams are unstable to small perturbations, leading to huge eddies (storms and fronts) that finish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



Mean Temperatures



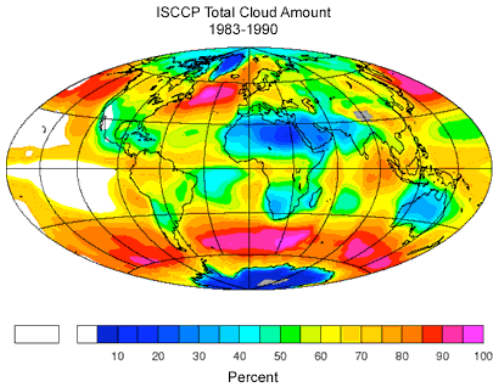
- Latitude dependence
- Seasonality
- Continentality
- Ocean currents



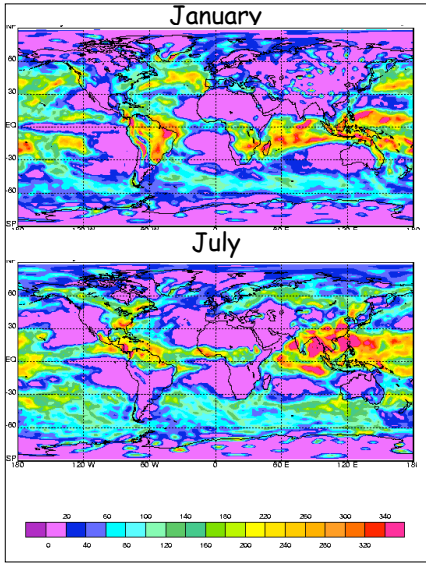
Sealevel Pressure

- Winter highs over cold continents
  - Antarctica!!
  - Siberia!
  - North America
- Winter lows over warmer oceans
  - Southern Ocean!!
  - Icelandic low
  - Aleutian low
- Summer (monsoon) lows over hot land
- Persistent highs over subtropical oceans

Atmospheric Cloudiness



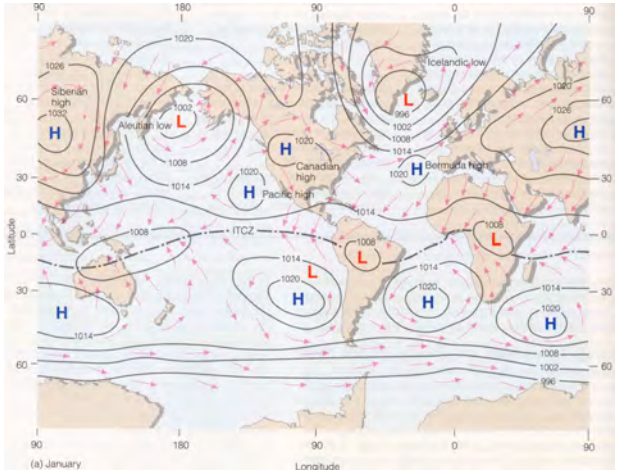
- Persistent clouds over ITCZ
- Cloudiest areas are over mid- to high-latitude oceans
- Clearest areas are subtropical highs



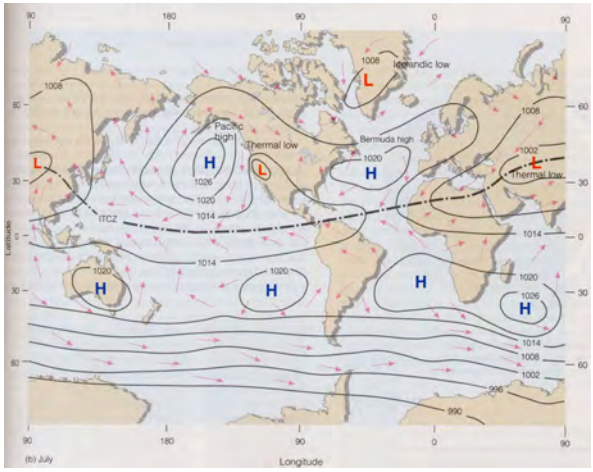
Precipitation
(mm/month)

- Very wet over tropics
- Seasonal shift (N/S)
- Monsoon regions
- Extremely dry subtropical highs
- Midlatitudes get more summer rain
- July rainfall looks like a map of forest cover

Pressure and Surface Winds
January



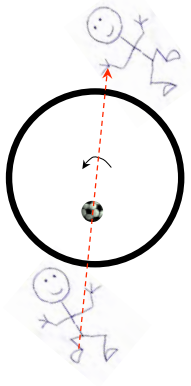
Pressure and Surface Winds
July



The Coriolis Barf Machine

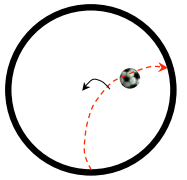
Remember these things?

Earth is Like a Barf Machine Too

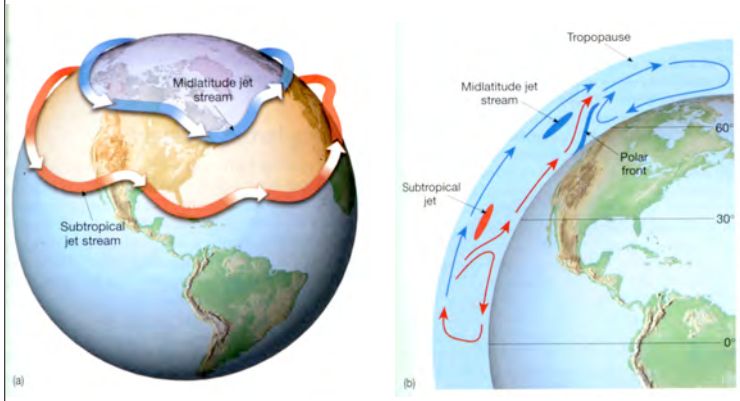


From the kids point of view, the ball goes in a straight line …

but from the point of view of the barf machine, the ball curves to the right as it passes over



Jet Streams



Planetary Waves and Poleward Energy Transport

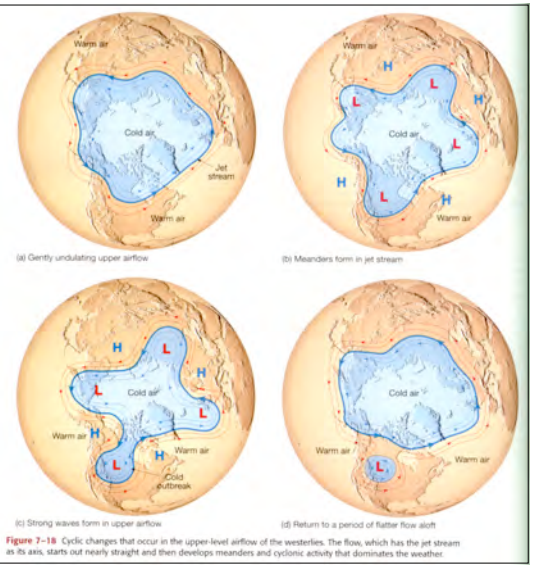


Figure 7–18 Cyclic changes that occur in the upper-level airflow of the westerlies. The flow, which has the jet stream as its axis, starts out nearly straight and then develops meanders and cyclonic activity that dominates the weather.

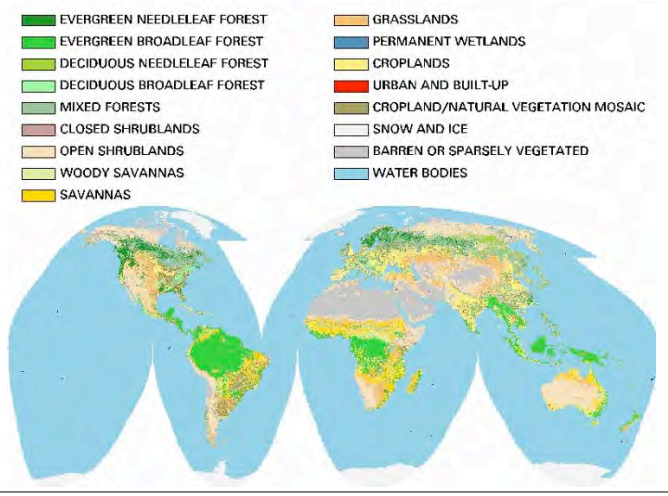
Climates of the World

- **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 in the winter

Other Influences:

Ocean currents, "continentality," vegetation, mountain ranges (altitude and orographic precipitation)

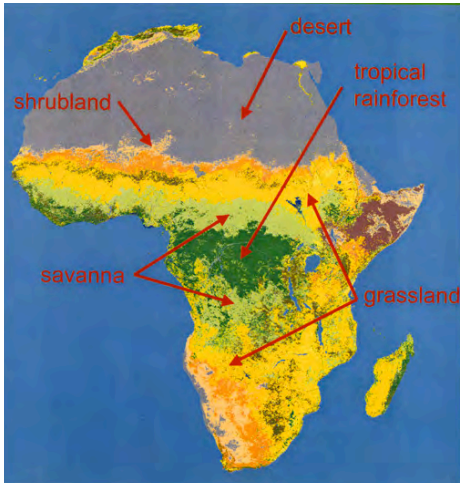
Classification of Land Vegetation



Land Use (Percentage of Total Land Area)

Land use	Percent
Arable mixed farming and human areas	10–13
Grazing land	20–25
Extratropical forests (mostly conifer)	10–15
Tropical forests and woodlands	13–18
Deserts	25–30
Tundra, high latitude	6–9
Swamp and marshes, lakes and streams	2–3

Tropical and Subtropical Vegetation

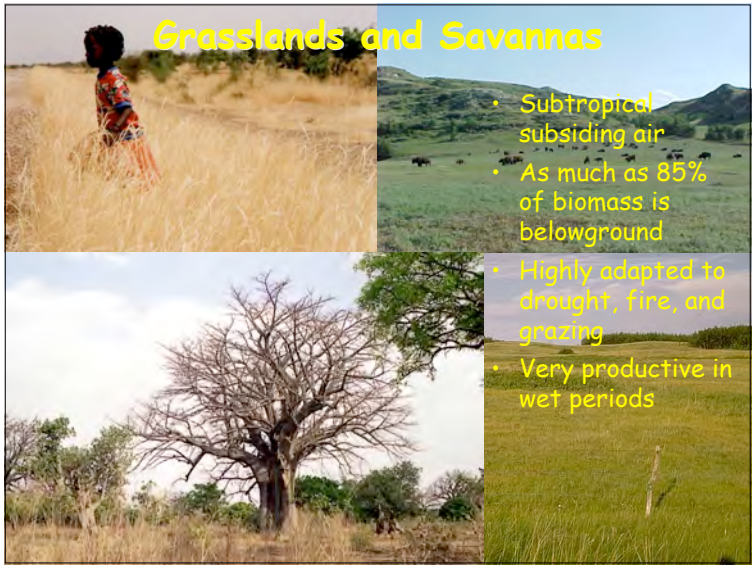


- Rainfall and its seasonal distribution determine the distribution of plant types
- Savannas and grasslands are adapted to seasonal and longer dry periods
- Landscape patterns strongly influence radiation budgets and climate

Tropical Forest

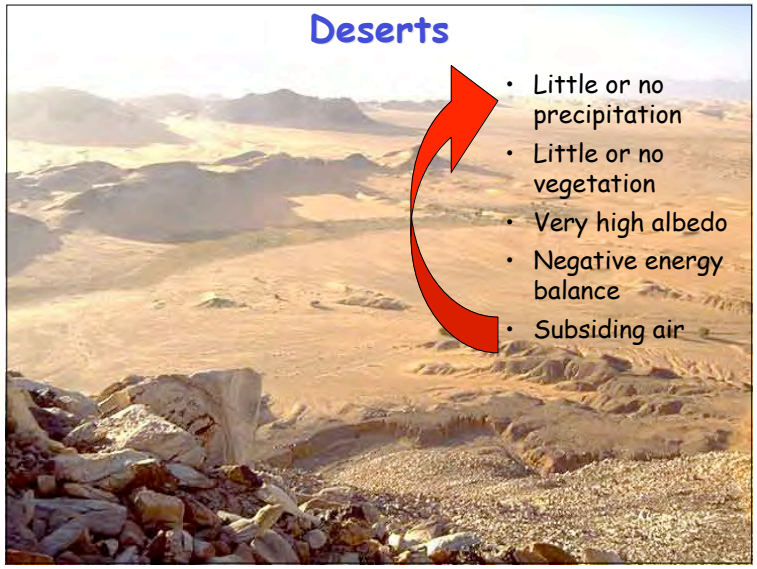
- Located in equatorial zone of mean rising motion and heavy precipitation during much of the year
- Low albedo, very strong energy absorption
- Broadleaf evergreen trees with extensive understory, as many as 300 tree species per km^2
- The most productive ecosystems on Earth
- Some are very deeply rooted (> 10 m) and can withstand periods of severe drought

Grasslands and Savannas



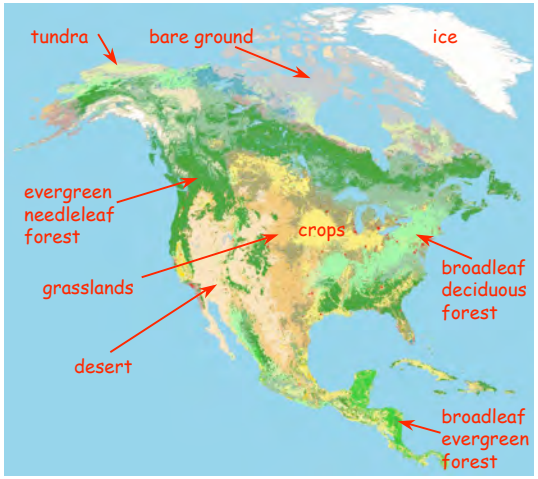
- Subtropical subsiding air
- As much as 85% of biomass is belowground
- Highly adapted to drought, fire, and grazing
- Very productive in wet periods

Deserts



- Little or no precipitation
- Little or no vegetation
- Very high albedo
- Negative energy balance
- Subsiding air

Temperate and Boreal Vegetation

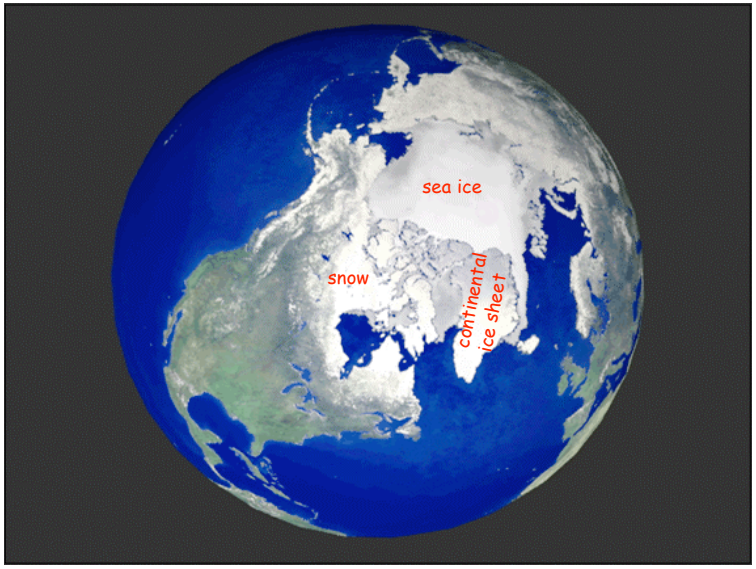


- Moisture, growing season, and human land use play roles
- Latitude and continentality are both very important

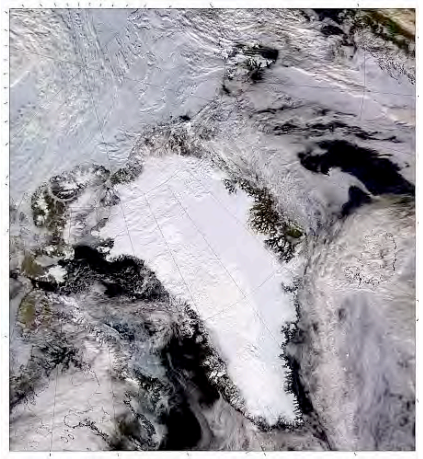

Broadleaf Deciduous Forest
Acewallpapers.com
Very productive forests located in midlatitudes
Abundant precipitation, but growing season limited by long cold winters
Leaf-area equals that of tropical forests during growing season


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

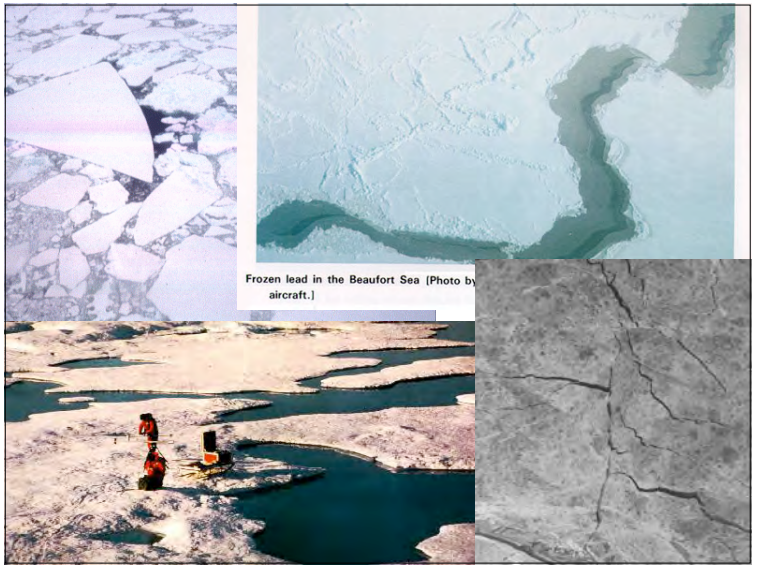

Tundra
High latitudes: cold dry climates, but very little evaporative demand, so surface may be very wet
Underlain by permafrost in many places
Low-growing, non-woody plants
Very short growing season
Supports migratory mammals


sea ice
snow
continental ice sheet

Continental and Sea Ice



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



Ross Ice Shelf

- Where the ice sheet meets the sea
- New York looked like this 18,000 years ago!