Global and Synoptic Scale Circulation Systems

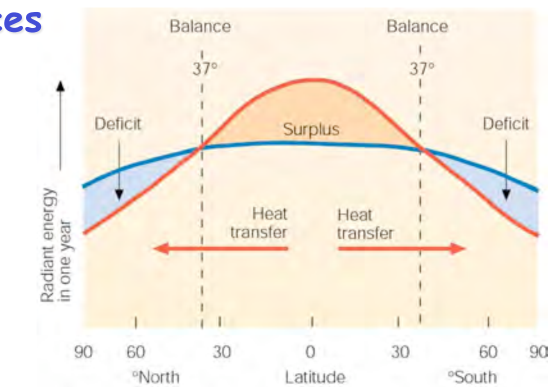
Poleward energy transport on a rotating sphere

Hadley cells and Ferrel cells

Polar vortex and midlatitude jet streams

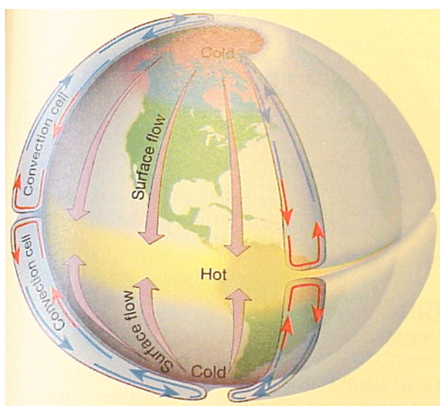
Midlatitude cyclones as waves

The circulations of the atmosphere and oceans are ultimately driven by solar and longwave radiation imbalances

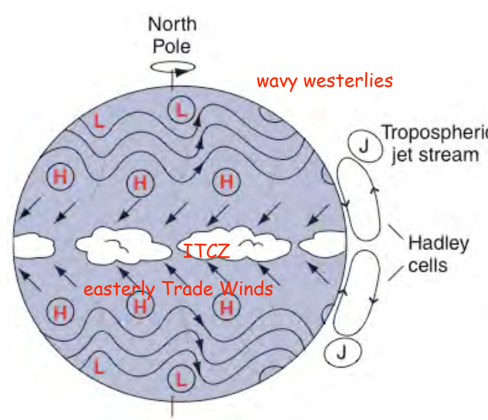


If the Earth didn't rotate, it would be easy for the flow of air to balance the energy

- 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



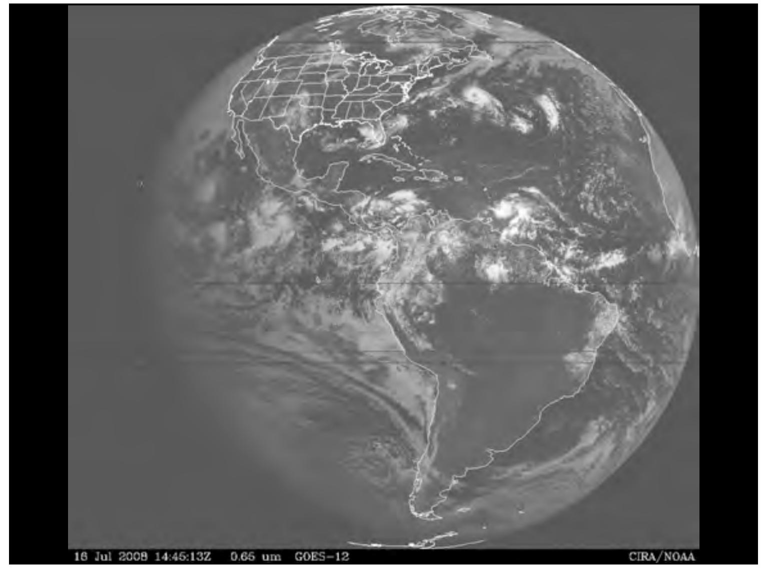
Wind Patterns on the Rotating Earth



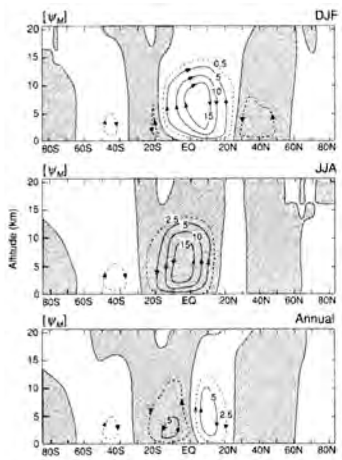
- Deep thermally direct convective cells confined to tropics
- Condensation heating in rising branch of Hadley Cell lifts the center of mass of the atmosphere (converts latent to potential energy)
- Downhill slope toward winter pole produces jet streams in middle latitudes
- Jet is unstable to small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

Key Features of 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; ITCZ
- **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*



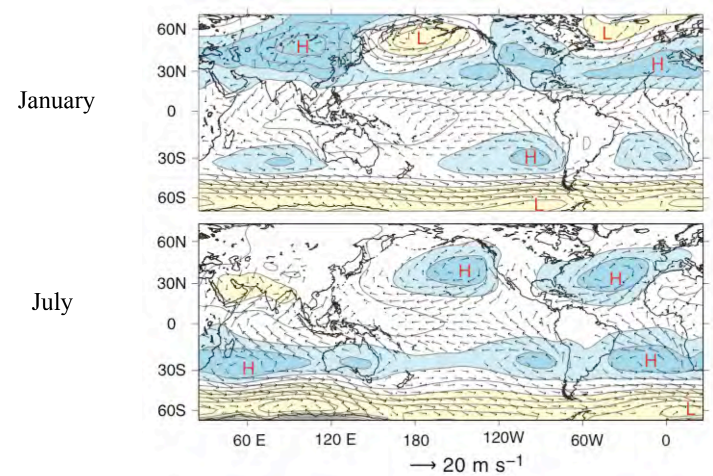
South-North Cross Sections



Mean meridional mass streamfunction (10^{10} kg s^{-1})

- Strongest feature is the Hadley Cell
  - Rising air in tropics
  - Poleward flow aloft into winter hemisphere
  - Sinking air in winter subtropics
  - Surface flow equatorward
  - Rising branch slightly displaced into summer hemisphere
- Much weaker Ferrel Cells in middle latitudes
  - "Thermally indirect"
  - A byproduct of much stronger eddy fluxes

Surface Winds and Pressure

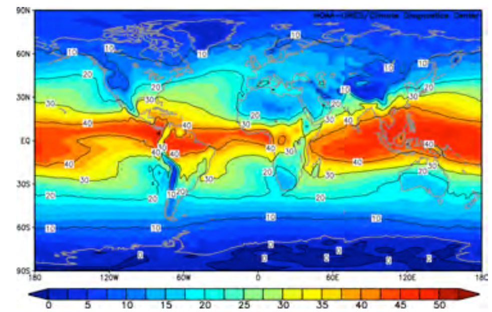


Understanding the Atmospheric Circulation

1. Driven by differential solar heating between the equator and poles. Atmospheric general circulation acts to move heat poleward.
2. In Hadley cell, warmer air rises and moves poleward. Equator-to-pole Hadley cell is impossible in the presence of rotation
3. In the Northern Hemisphere, air is deflected to the right as it moves; in the Southern Hemisphere, it is deflected toward the left.
   - rotation produces trade winds; surface westerlies in NH; upper tropospheric jets.
4. Ferrel cell is the "zonal mean" response to poleward heat and momentum fluxes by eddies. It runs backwards! Transports heat the wrong way!

Atmospheric Water

annual mean precipitatble water (mm)

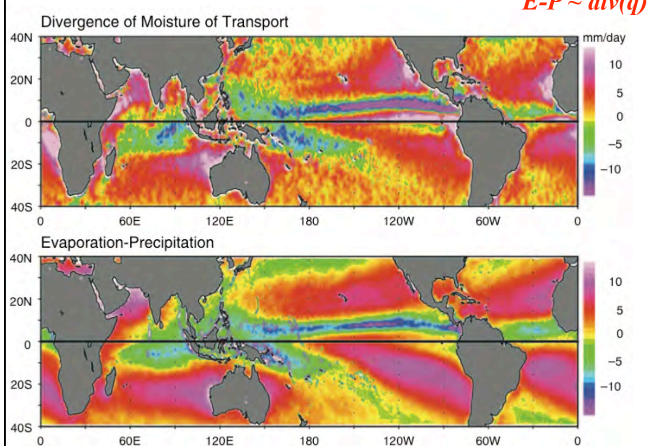


- Mean ~ 25 mm (1 inch)
- Mean precip rate is about 2.6 mm/day
- Residence time ~ 9 days
- Very steady
- E ~ P ~ 2.6 mm/day

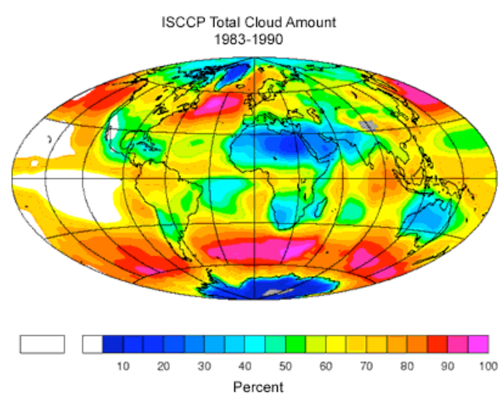
Source **http://www.cdc.noaa.gov/**
Reanalysis for *1968-1996*

Vapor, Winds, and Rainfall

E-P ~ div(q)



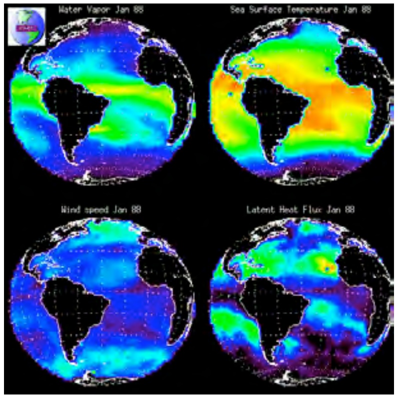
Atmospheric Cloudiness



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

Sources of Atmospheric Water

- Water vapor is concentrated in the tropics
- Evaporation from the sea surface depends on *radiation, humidity, and wind*
- The greatest water source is in the *subtropics*, with near zero evaporation in the ITCZ

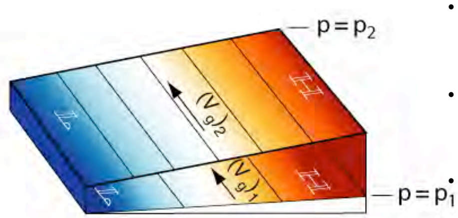


Energy in the Global Atmosphere

Name	Symbol	Formula	Amount × 10^6 J m^{-2}	% of total
Internal energy	IE	$c_v T$	1800	70
Potential energy	PE	gz	700	27
Latent energy	LH	Lq	70	2.7
Kinetic energy	KE	$\frac{1}{2}(u^2 + v^2)$	1.3	0.05
Total energy	IE + PE + LH + KE		2571	100

- Four kinds of energy: heat/enthalpy and gravitational potential account for 97%
- Kinetic energy is small but very important for moving the others around!
- Much of the energy is unavailable for conversion (atmosphere "holding itself up")
- Circulation responds to energy (temperature) gradients on constant pressure surfaces

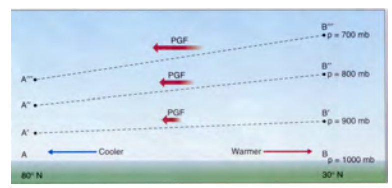
Thermal Wind Balance Produces Jets

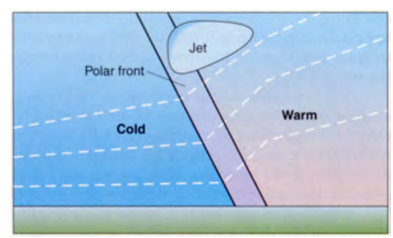


- Hadley Cell imports water vapor from the subtropics
- Heavy rain in ITCZ converts latent to sensible heat
- This raises the center of mass of the tropical atmosphere (converts sensible to potential energy)

- Geostrophic wind changes with height are proportional to the N-S gradient in temperature
- Hot tropics and cold poles produce westerly jet streams at middle latitudes

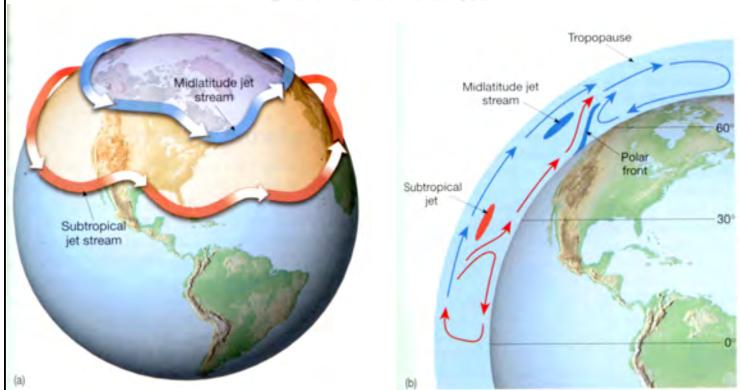
Baroclinicity and the Polar Front Jet





- Air density depends on temperature
- Warm air occupies more vertical space per mass (pressure depth)
- Tilt of pressure surfaces increases with height
- Coriolis force produces wind flow into screen
- Wind max (jet stream) occurs above steepest temperature gradient

Jet Streams



- Subtropical Jet is zonal mean response to poleward flow in upper branch of Hadley Cell
- Polar front jet is response to meridional temperature gradients

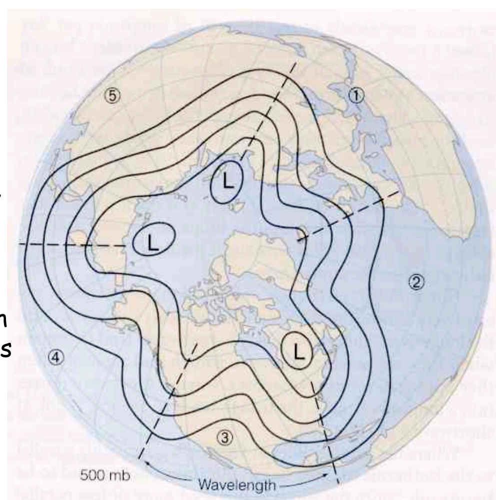
Extratropical storms are Eddies in the Jet Stream

- Momentum is *transferred from the earth* to the atmosphere in the *trade wind belt*.
- Momentum is *transferred from the atmosphere to the earth in the midlatitudes*.
- If the earth is always trying to slow down the midlatitude westerlies, why don't they weaken and disappear over time?
  - Eddies (storms) transfer momentum poleward in the upper troposphere.
  - This momentum transfer weakens the Hadley circulation, but drives the Ferrel cell.

Waves on the polar vortex

Hemispheric westerlies typically organized into 4-6 "long waves"

Wind blows through them, but the waves themselves propagate slowly (east to west!) or not at all



Planetary Waves and Poleward Energy Transport

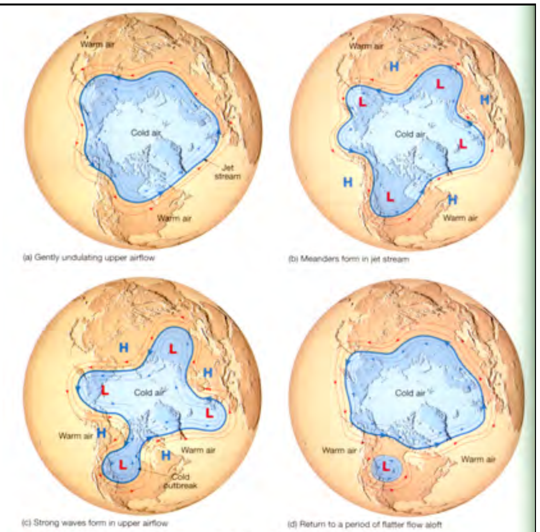
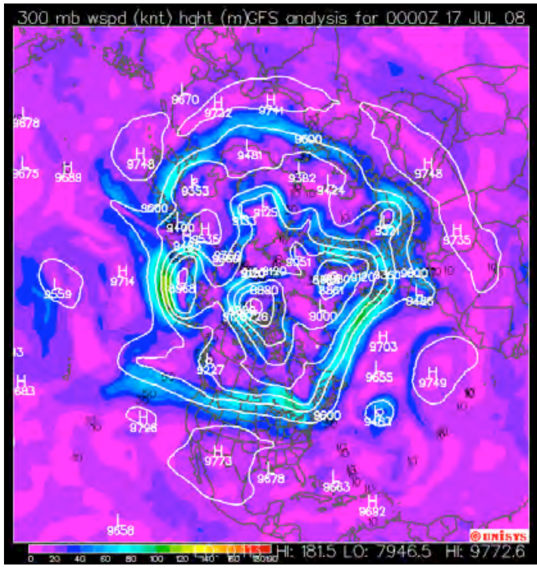


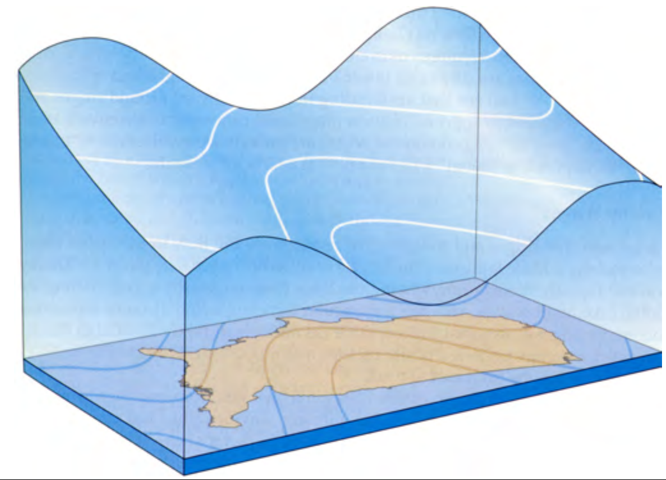
Figure 7–18 Cyclic changes that occur in the upper-level airflow of the westerlies. The flow, which has the jet stream as its axis, starts out nearly straight and then develops meanders and cyclonic activity that dominates the weather.



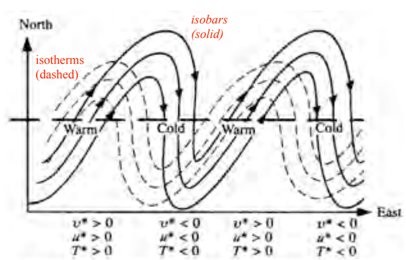
Today @ 300 mb

- "Bowl-shaped" height contours
- Zonal flow over USA
- Aleutian Low
- Jet streaks

Developing Transient Wave



Northward Heat Flux by Eddies



- Why do the eddies work this way?
- What does this configuration do to the eddies themselves?

- Temperature wave tends to be displaced westward relative to pressure wave (especially at lower levels)
- Warm air moves north, cold air moves south
- Both cause northward heat transport

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

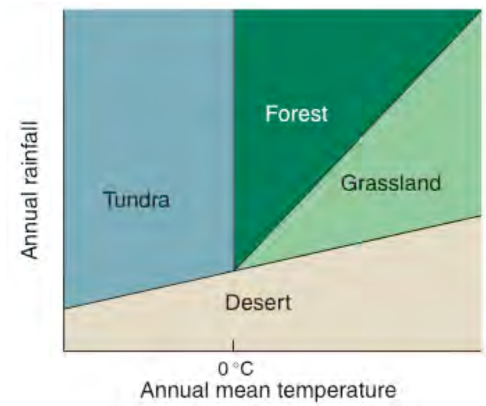
Climates of the World

- **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 in the winter

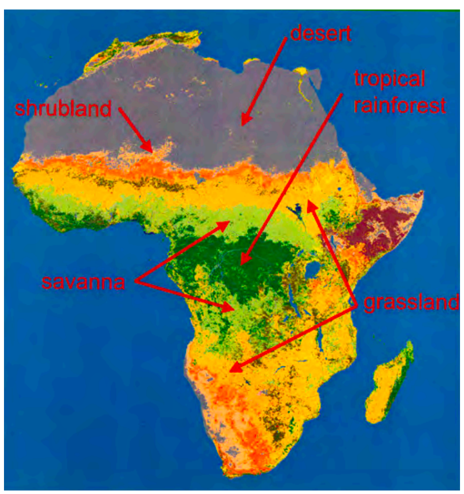
Other Influences:

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

Patterns of Climate and Vegetation



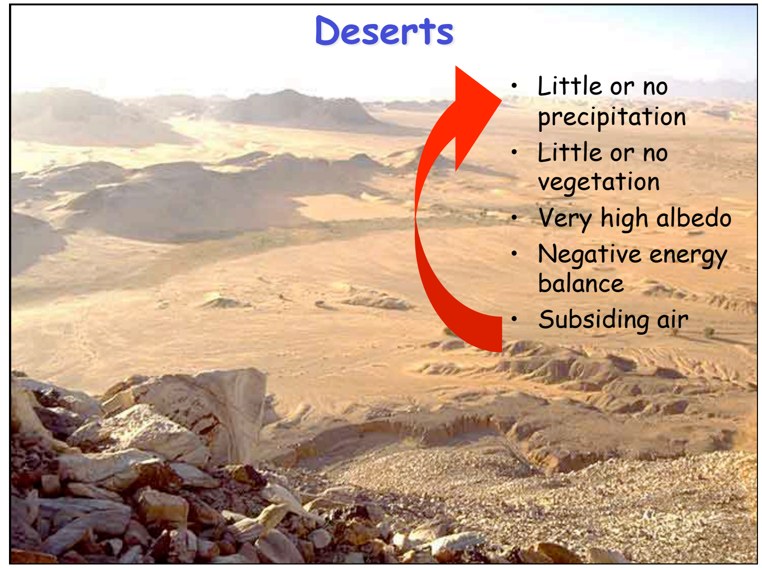
Tropical and Subtropical Vegetation

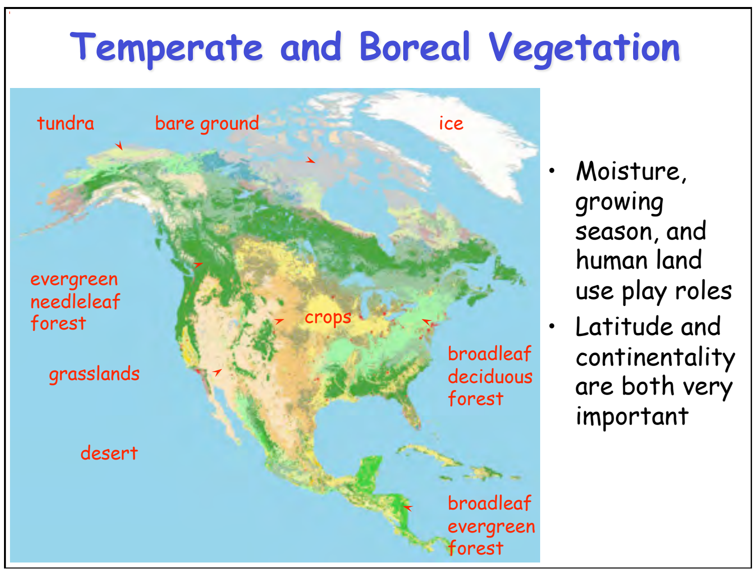


- Rainfall and its seasonal distribution determine the distribution of plant types
- Savannas and grasslands are adapted to seasonal and longer dry periods
- Landscape patterns strongly influence radiation budgets and climate

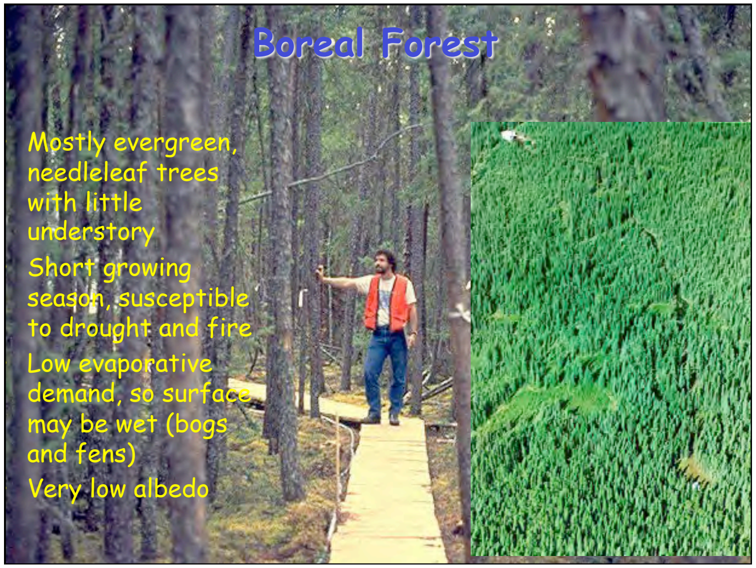
Tropical Forest


Grasslands and Savannas
• Subtropical subsiding air
• As much as 85% of biomass is belowground
• Highly adapted to drought, fire, and grazing
• May be very productive in rare wet periods


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


Temperate and Boreal Vegetation
tundra
bare ground
ice
evergreen needleleaf forest
crops
grasslands
broadleaf deciduous forest
desert
broadleaf evergreen forest
• Moisture, growing season, and human land use play roles
• Latitude and continentality are both very important


Broadleaf Deciduous Forest
• 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



The Big Picture

- The general circulation transports energy upward and poleward to balance radiational losses to space
- The Earth's rotation complicates this!
- The Hadley cell imports water vapor and condenses it to lift the tropical atmosphere, tilting pressure surfaces toward the poles
- The resulting polar vortex is unstable, producing waves in the jets that allow energy transport across the midlatitudes (and which also control winter weather!)