What Makes the Wind Blow?

Three real forces (gravity, pressure gradient, and friction) push the air around

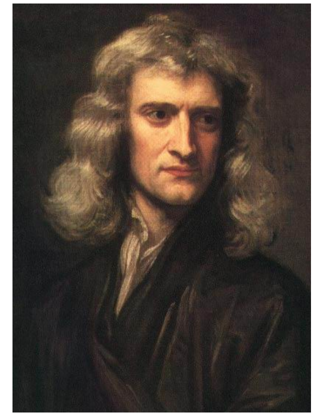
Two apparent forces due to rotation (Coriolis and centrifugal)

Large-scale flow is dominated by gravity/pressure and Coriolis …
friction and centrifugal important locally

Newton

$$\sum \vec{F} = m\vec{a}$$

- Objects stay put or move uniformly in the same direction unless acted on by a force
- Acceleration is a result of the sum (net) of forces, in the vector sense



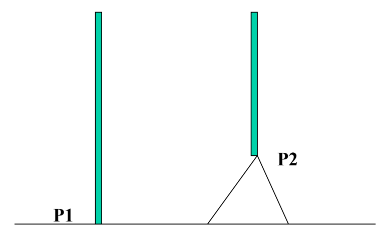
Forces Acting on the Air

- Pressure gradient force (pushing)
- Gravity (falling)
- Friction (rubbing against the surface)

- "Apparent" forces
  - The Coriolis Force
  - Centrifugal Force

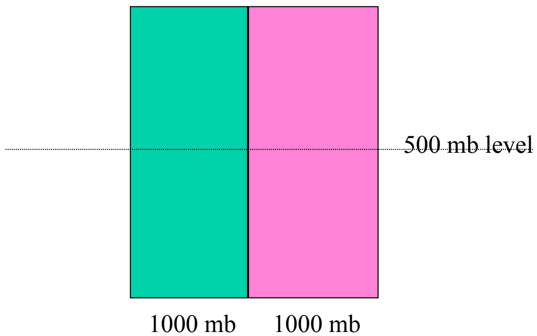
Why does pressure vary horizontally?

- Elevation changes cause pressure differences
- These are balanced by gravity and don't cause wind to blow
- *But why does pressure vary between locations which are at the same elevation?*

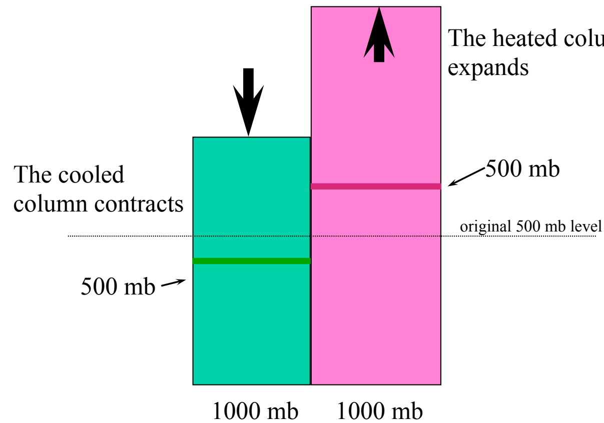


Thought Experiment:

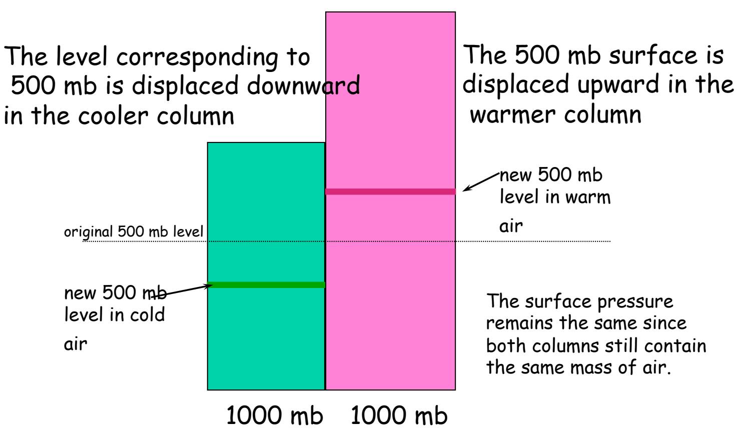
Consider two columns of air with the same temperature and distribution of mass



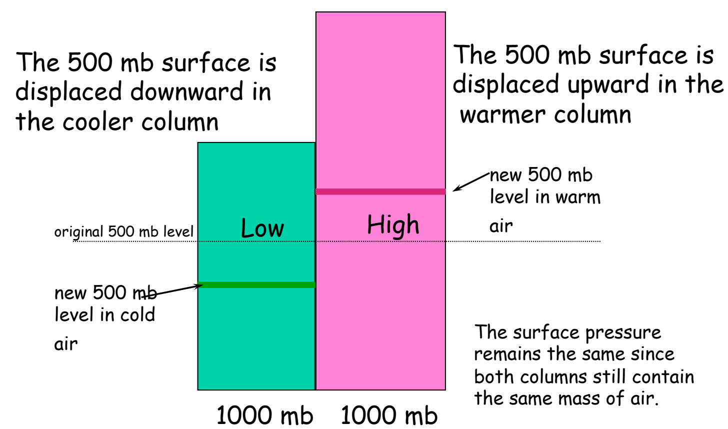
Now cool the left column and heat the right



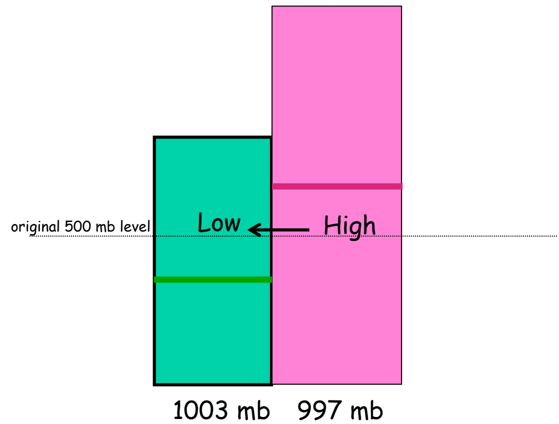
The level of the 500 mb surface changes; the surface pressure remains unchanged



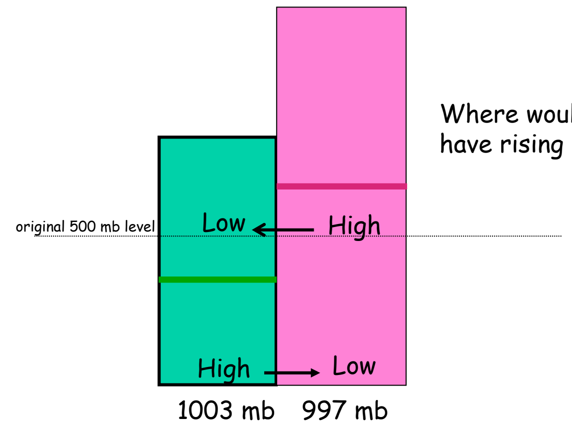
A pressure difference in the horizontal direction develops above the surface



Air moves from high to low pressure in the middle of the column, causing the surface pressure to change.



Air moves from high to low pressure at the surface…



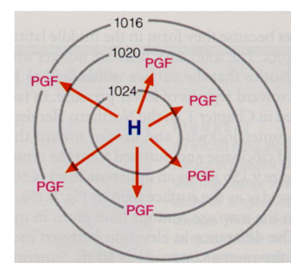
Where would we have rising motion?

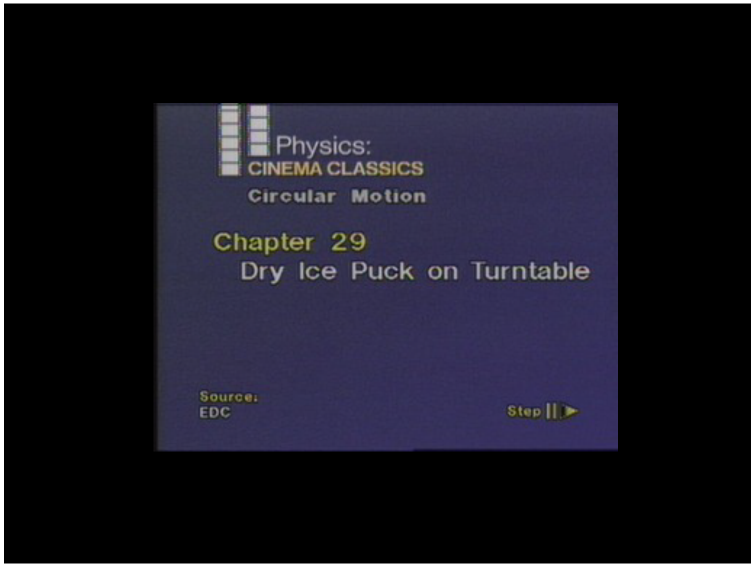
Thought Experiment Review

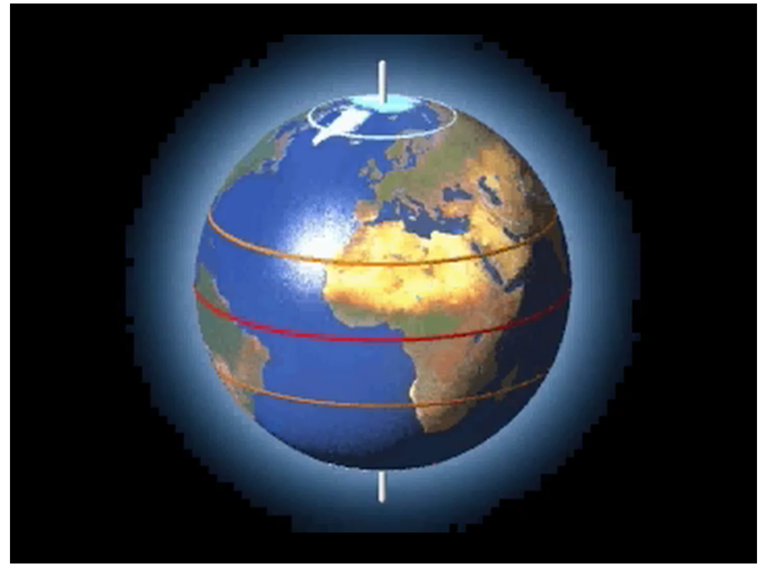
- Starting with a uniform atmosphere at rest, we introduced differential heating
- The differential heating caused different rates of expansion in the fluid
- The differing rates of expansion resulted in pressure differences aloft along a horizontal surface.
- The pressure differences then induced flow (wind!) in the fluid
- This is a microcosm of how the atmosphere converts differential heating into motion

Pressure Gradient Force

- Magnitude
  - Inversely proportional to the distance between isobars or contour lines
    - The closer together, the stronger the force
- Direction
  - Always directed toward lower pressure





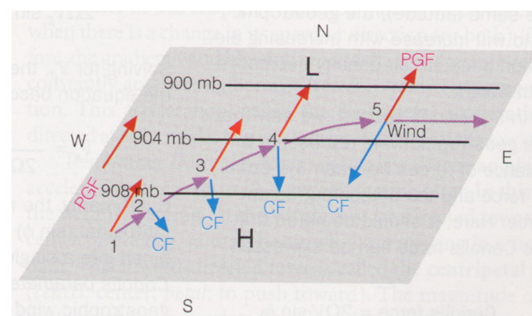


Coriolis Force

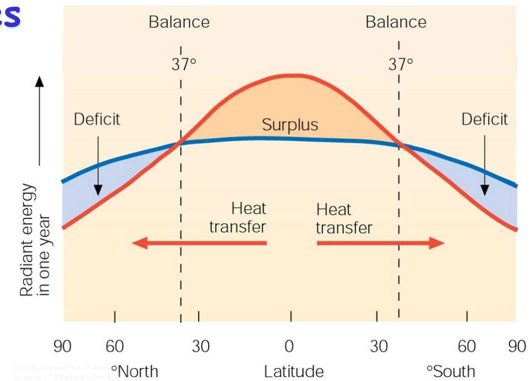
- Magnitude
  - Depends upon the latitude and the speed of movement of the air parcel
    - The higher the latitude, the larger the Coriolis force
      - zero at the equator, maximum at the poles
    - The faster the speed, the larger the Coriolis force
- Direction
  - The Coriolis force always acts at right angles to the direction of movement
    - To the right in the Northern Hemisphere
    - To the left in the Southern Hemisphere

Coriolis Force

- Acts to right in northern hemisphere
- Proportional to wind speed

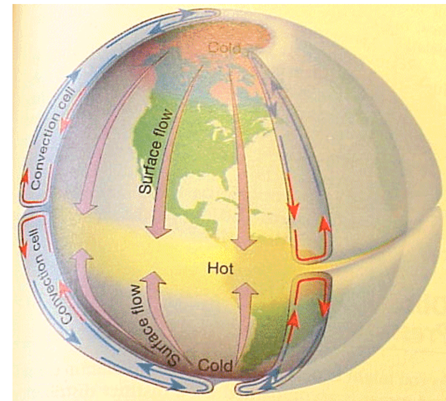


The circulations of the atmosphere and oceans are ultimately driven by solar and longwave radiation imbalances

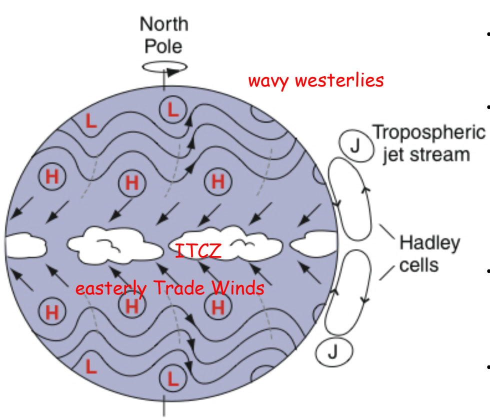


If the Earth didn't rotate, it would be easy for the flow of air to balance the energy

- 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



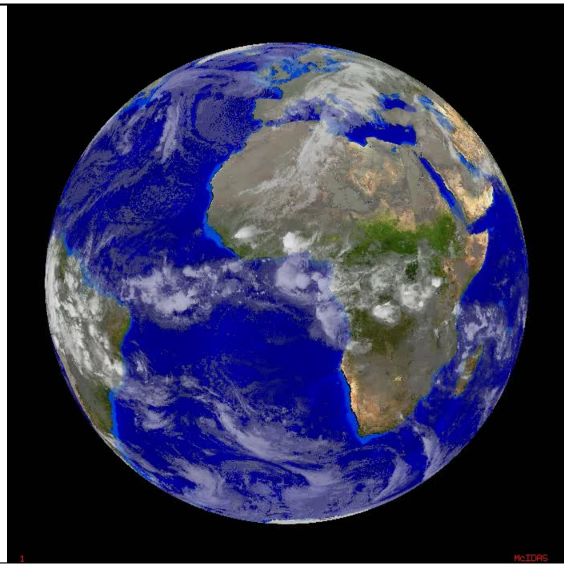
Wind Patterns on the Rotating Earth



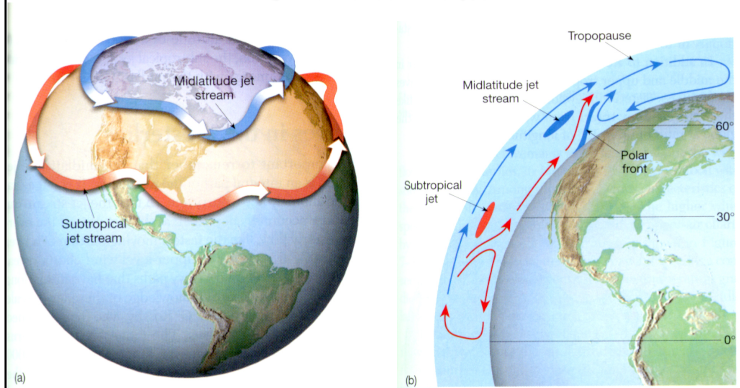
- Deep thermally direct convective cells confined to tropics
- Condensation heating in rising branch of Hadley Cell lifts the center of mass of the atmosphere (converts latent to potential energy)
- Downhill slope toward winter pole produces jet streams in middle latitudes
- Jet is unstable to small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



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

Atmospheric Circulation
in a nutshell

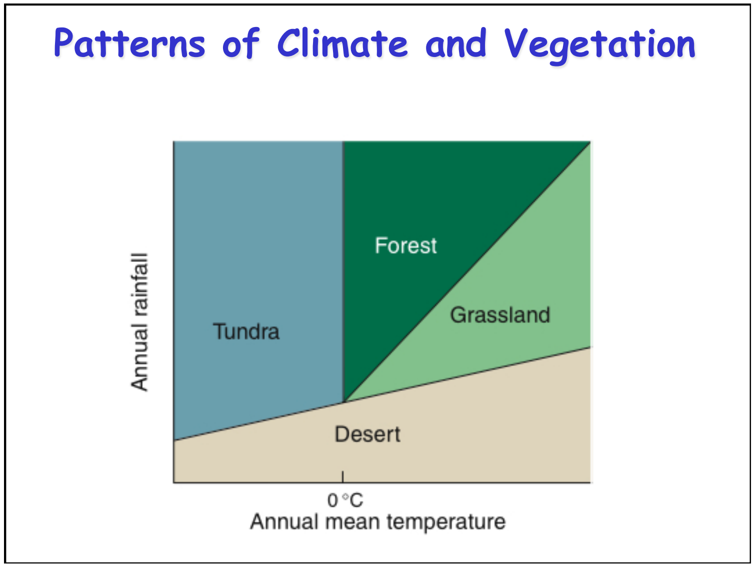
- Hot air rises (rains a lot) in the tropics
- Air cools and sinks in the subtropics (deserts)
- Poleward-flow is deflected by the Coriolis force into westerly jet streams in the temperate zone
- Jet streams are unstable to small perturbations, leading to huge eddies (storms and fronts) that finish the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

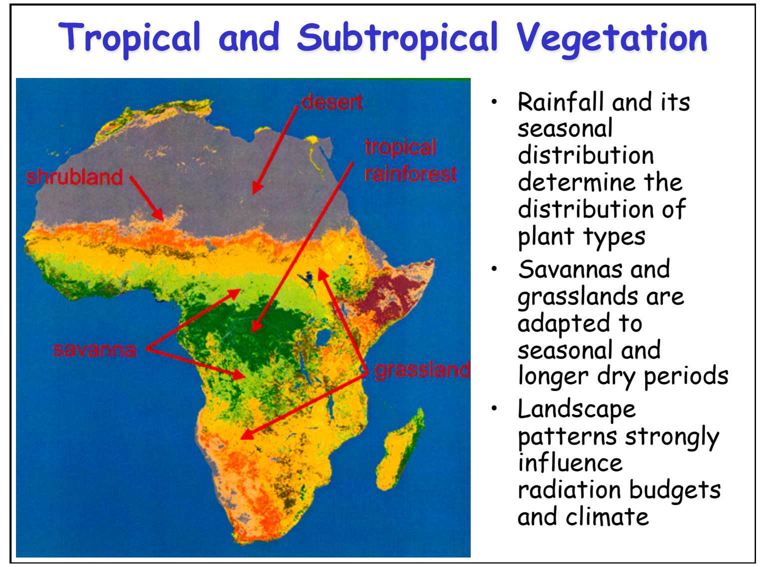
Climates of the World

- **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

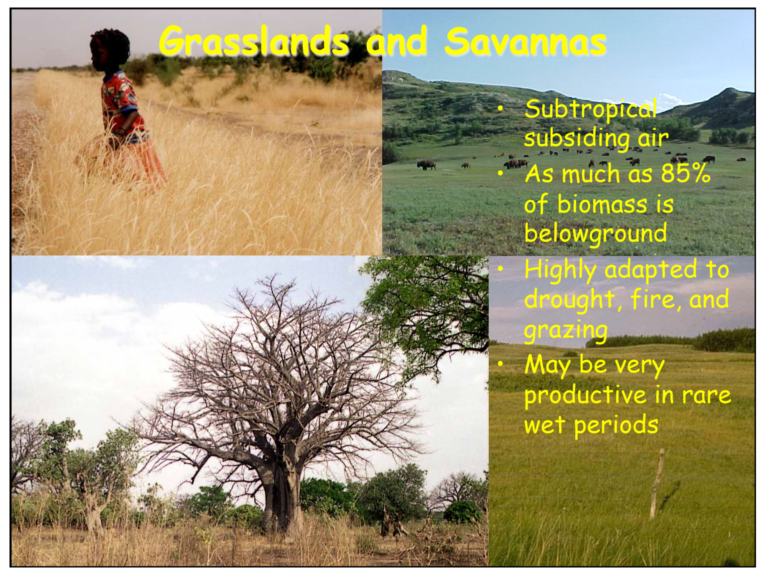
Other Influences:

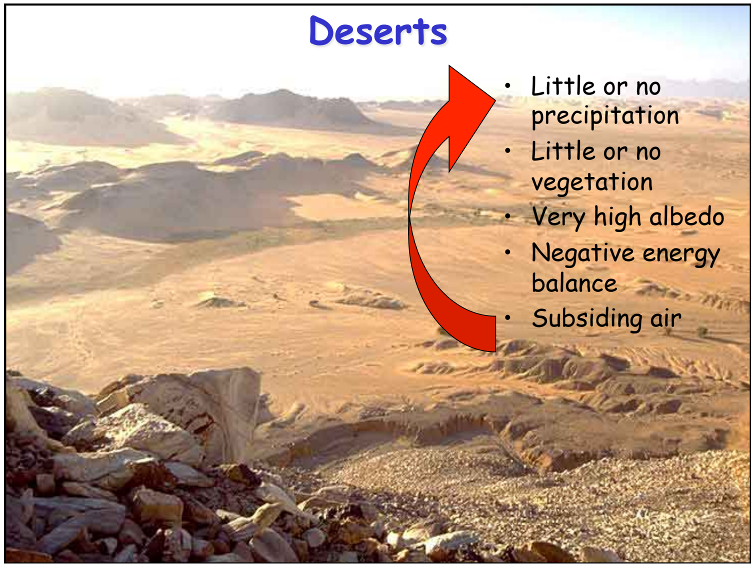
Ocean currents, "continentality," vegetation, mountain ranges (altitude and orographic precipitation)

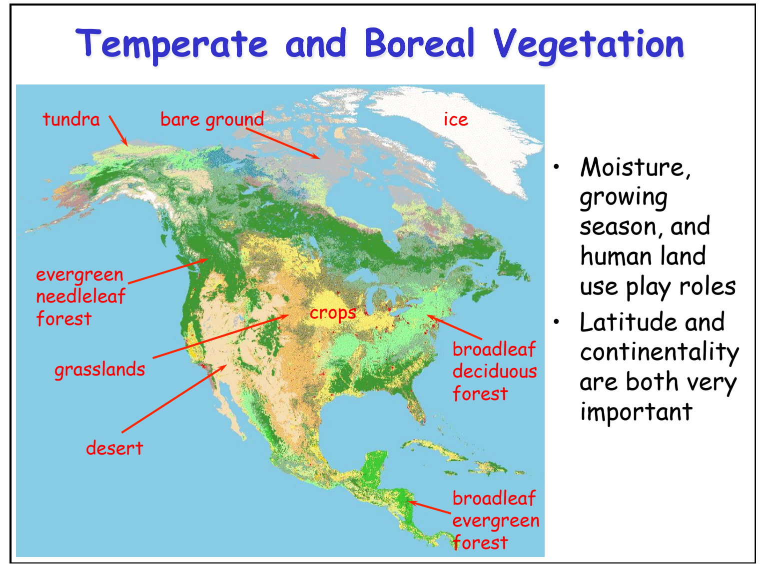

Patterns of Climate and Vegetation
Forest
Grassland
Tundra
Desert
Annual rainfall
0 °C
Annual mean temperature


Tropical and Subtropical Vegetation
desert
tropical rainforest
shrubland
savanna
grassland
• 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

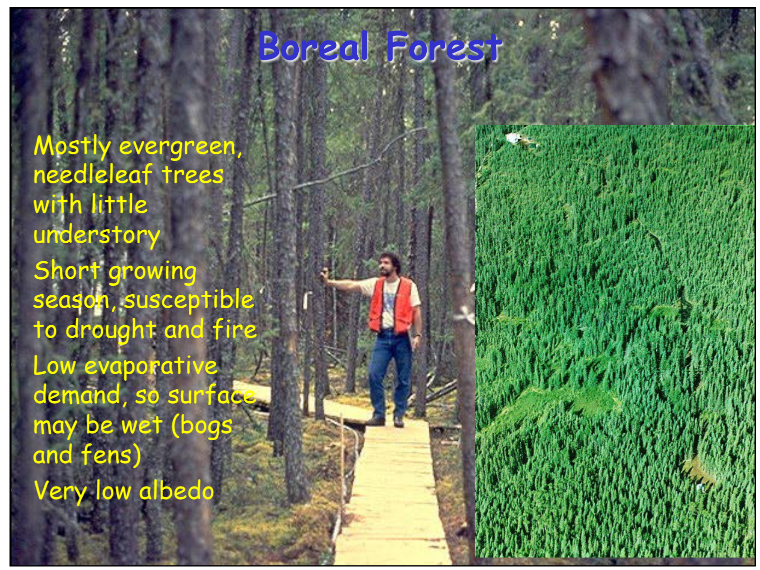

Tropical Forest
Located in equatorial zone of mean rising motion and heavy precipitation during much of the year
Low albedo, very strong energy absorption
Broadleaf evergreen trees with extensive understory, as many as 300 tree species per km^2
The most productive ecosystems on Earth
Some are very deeply 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
• 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
broadleaf deciduous forest
grasslands
desert
broadleaf evergreen forest
Moisture, growing season, and human land use play roles
Latitude and continentality are both very important

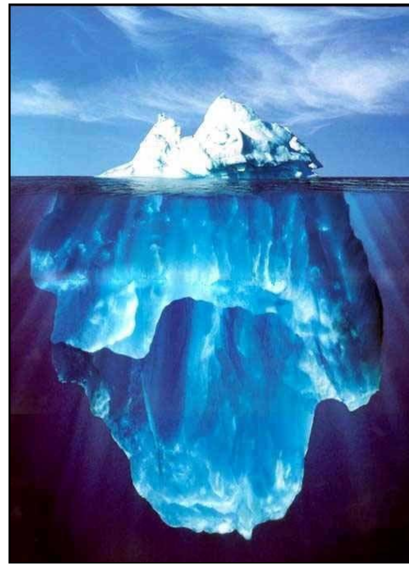

Broadleaf Deciduous Forest
Acewallpapers.com
Very productive forests located in midlatitudes
Abundant precipitation, but growing season limited by long cold winters
Leaf-area equals that of tropical forests during growing season


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

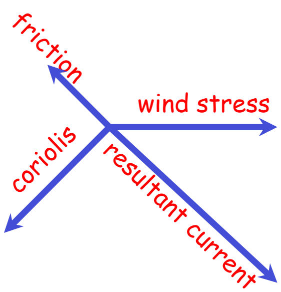
Tundra

- 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

Icebergs



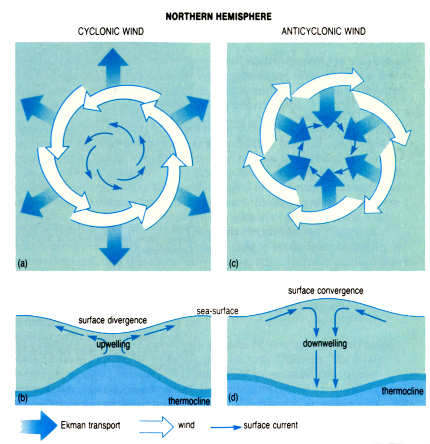
Surface Balance of Forces



- Wind stress accelerates surface water
- Friction couples surface to underlying water
- Friction always acts exactly opposite current motion
- Coriolis acceleration is always perpendicular to current motion

RESULT: Surface current directed about 45° (right/left) of wind in (NH/SH)

Ekman Pumping



- Ekman flow in NH is 90° to the right of the wind stress
- Cyclonic wind forces divergence in water, and upwelling
- Anticyclonic wind forces convergence and downwelling

Idealized Gyre

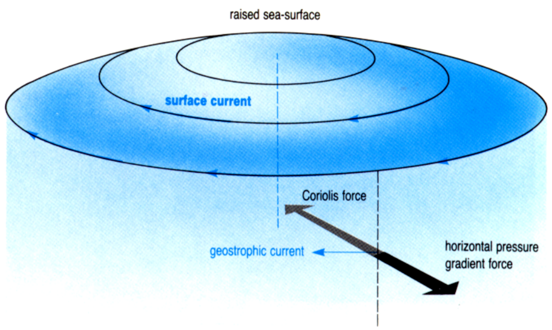
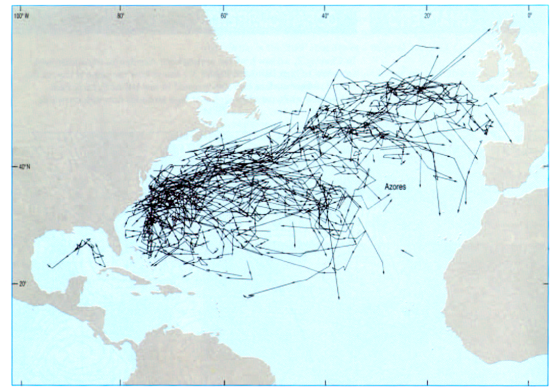


Figure 3.24 The generation of geostrophic current flow in a gyre driven by anticyclonic winds in the Northern Hemisphere. This current is driven by the wind only indirectly and persists below the wind-driven (Ekman) layer.

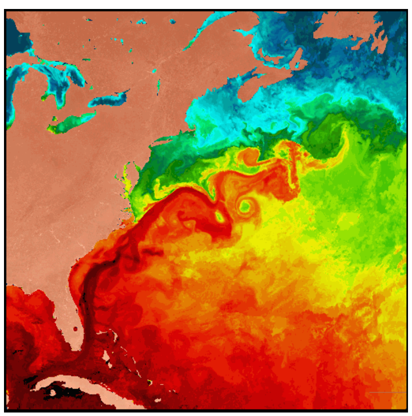
- Conver-gence of Ekman flow raises sea surface
- Rotating "dome" results

Is there a Gulf Stream?



Trajectories of derelict (drifting) ships (19th century)

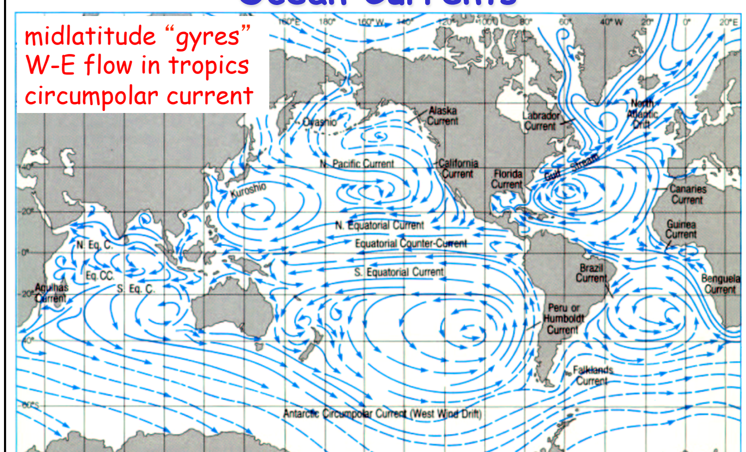
Sea-Surface Temperature from Space



- Note eddies and "rings" in Gulf Stream

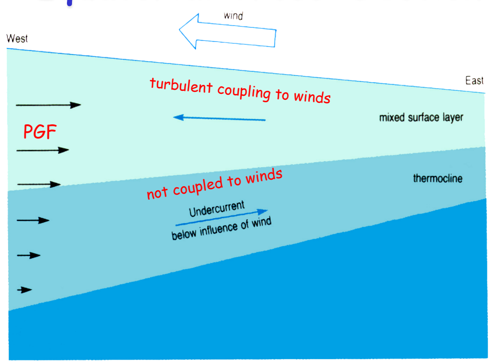
Ocean Currents

midlatitude "gyres"
W-E flow in tropics
circumpolar current



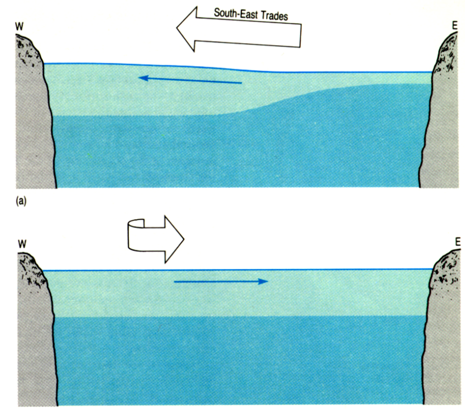
How are these known? Effects on poleward energy transport?

Equatorial Cross-Section



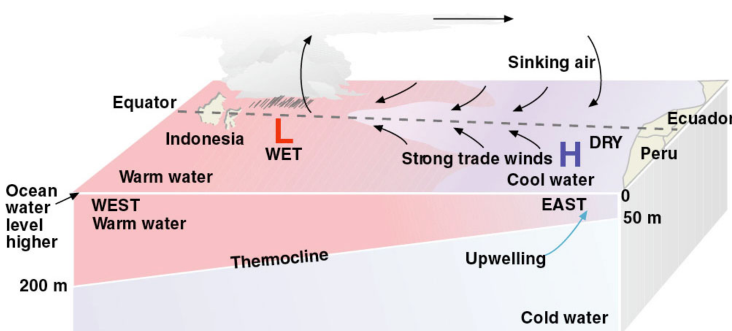
- Because there's no Coriolis force, wind pushes water west
- Cold water gets pushed "out of the way" (downward) as warm water "piles up" on top

El Niño



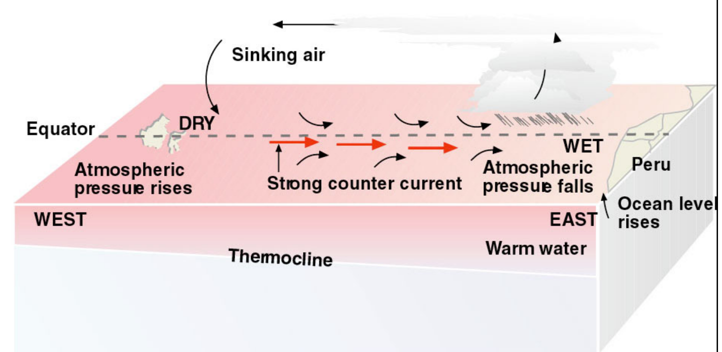
- Normal conditions: Huge accumulation of deep warm water in W. Pacific
- El Niño: Relaxation of Trade Winds allows warm water to flow eastward

Normal (non-El Niño) Conditions



- Surface water flow from east toward west
- Deep thermocline and warm water in western Pacific (associated deep convection & rainfall)
- Shallow thermocline and cool SST's in east Pacific

El Niño Conditions



- Surface water flow toward east
- Warm SSTs, convection & rainfall shift to central Pacific
- Warmer SST's in eastern Pacific

El Niño Southern Oscillation (ENSO)

- Southern Osciallation Index (SOI) is the difference in normalized surface pressure (how many std deviations from the mean) between Darwin, Australia and Tahiti
- Positive SOI anomaly: “El Niño”