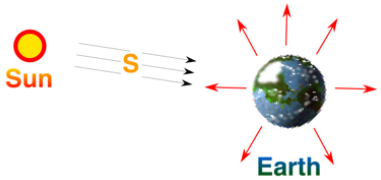
Course Outline

Climate 101

- 2/7 Introduction: The Earth System
- 2/14 Energy, Radiation, & Temperature
- 2/21 Winds, Currents, and Water
- 2/28 Climates of the Past
- 3/7 Modern Climate Change

Planetary Energy Balance



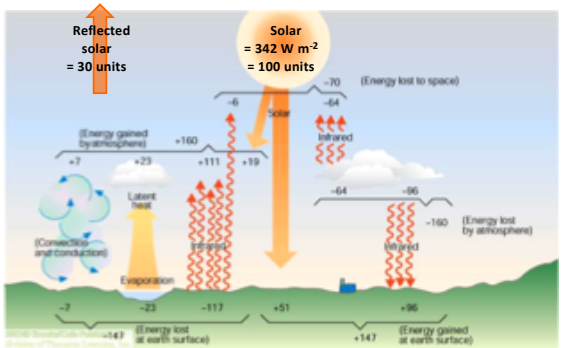
Energy In = Energy Out

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

$$T \approx -18^\circ\mathrm{C} = 0^\circ\mathrm{F}$$

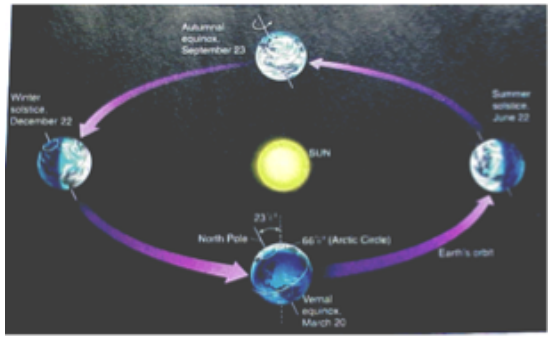
But the observed T_s is about 15° C (59° F)

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)

Earth's Orbit

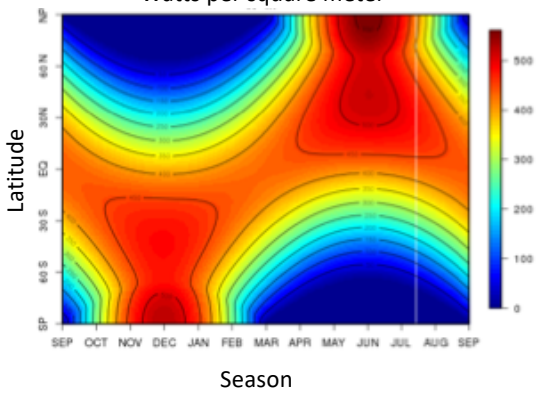


- Seasonally varying distance to sun has only a tiny effect on seasonal temperature
- The earth's orbit around the sun leads to seasons because of the tilt of the Earth's axis

Sunshine

Average Daily Radiation Above Atmosphere

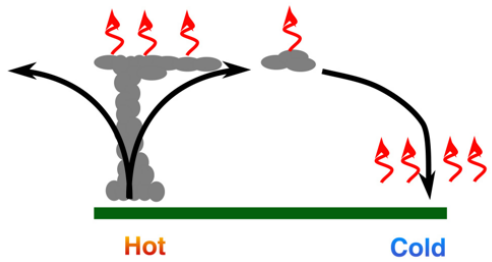
Watts per square meter



- 75° N in June gets more sun than the Equator!
- N-S gradient very strong in winter, very weak in summer
- Very little tropical seasonality

The Job of the Atmosphere

is to let the energy out!

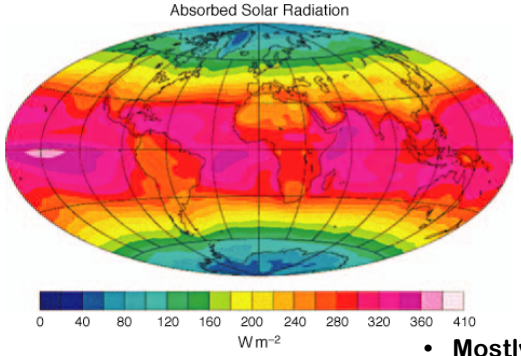


"Piles up" in tropics "Escapes" near poles and a

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

Energy In

Absorbed Solar Radiation

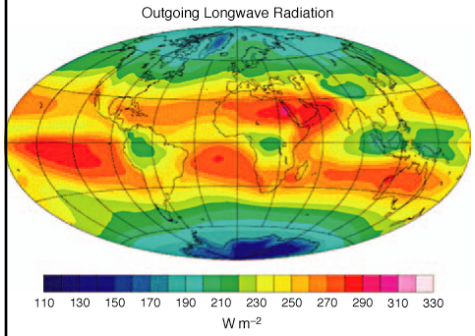


Annual Mean

- Mostly a map of latitude
- Land-sea contrast
- Ice and snow
- Deserts vs forests

Energy Out

Outgoing Longwave Radiation

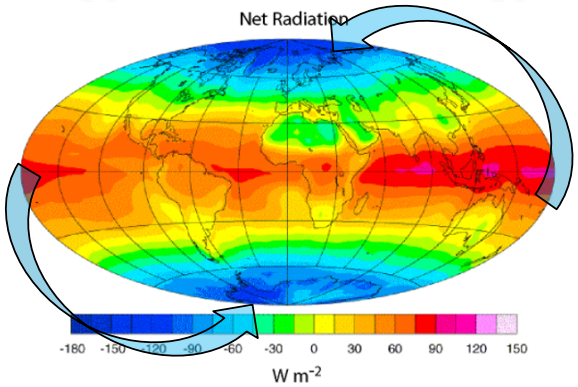


Annual Mean

Given by σT^4 (but which T?)

- Combined surface and atmosphere effects
- Decreases with latitude (cold)
- Greatest 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)

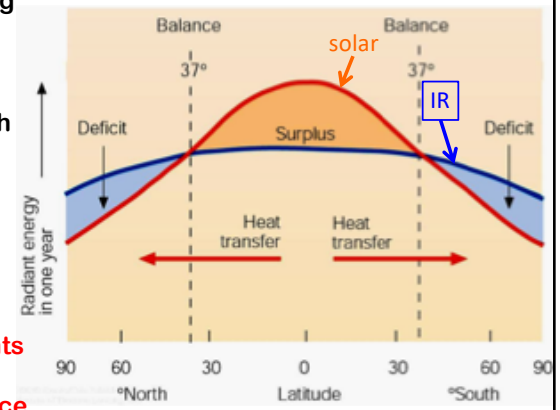
Energy In minus Energy Out



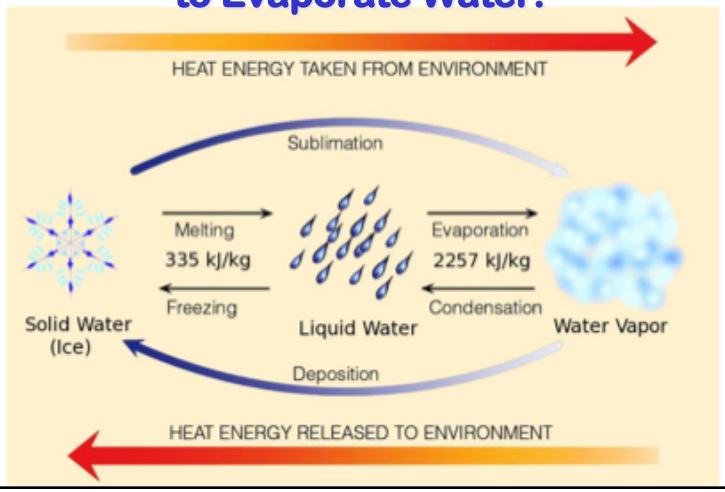
- Incoming solar minus outgoing longwave
- Must be balanced by *horizontal transport* of energy by atmosphere and oceans!

Earth's Energy Balance

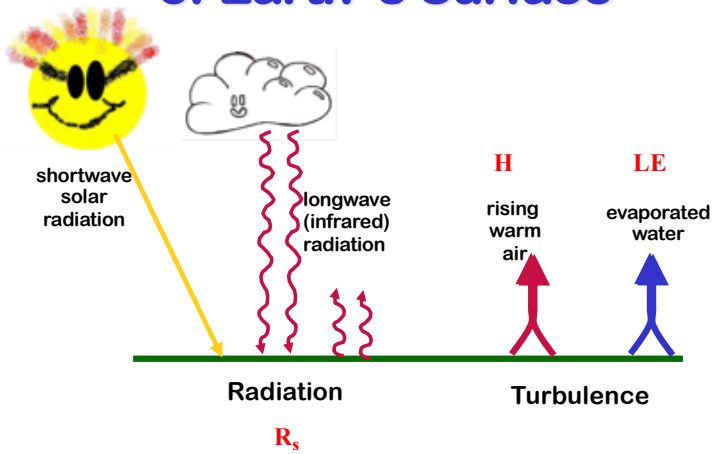
- Both incoming solar and outgoing longwave decrease with latitude
- Solar decreases faster
- Winds and ocean currents must make energy balance



It Takes a Lot of Energy to Evaporate Water!

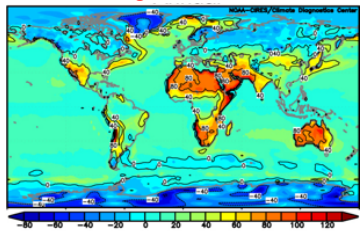


Energy Balance of Earth's Surface

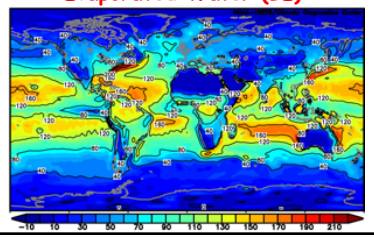


Convective Cooling at Surface

Rising Warm Air (H)



Evaporated Water (LE)



- Energy absorbed at the surface mostly emitted as IR (117 units)
- Most of the rest is used to evaporate water (23 units)
- Small residual warms the air

What Makes the Wind Blow?

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

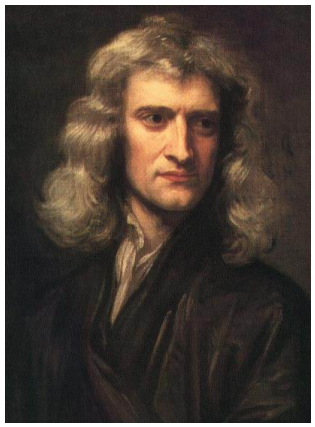
Two apparent forces due to rotation (Coriolis and centrifugal)

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

Isaac 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

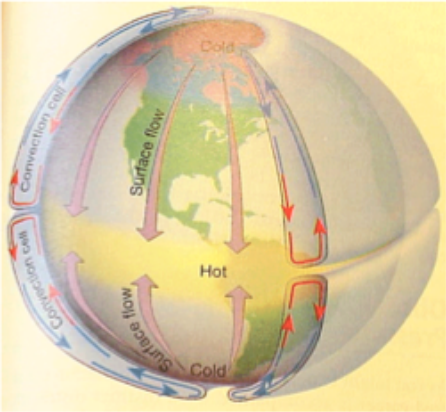


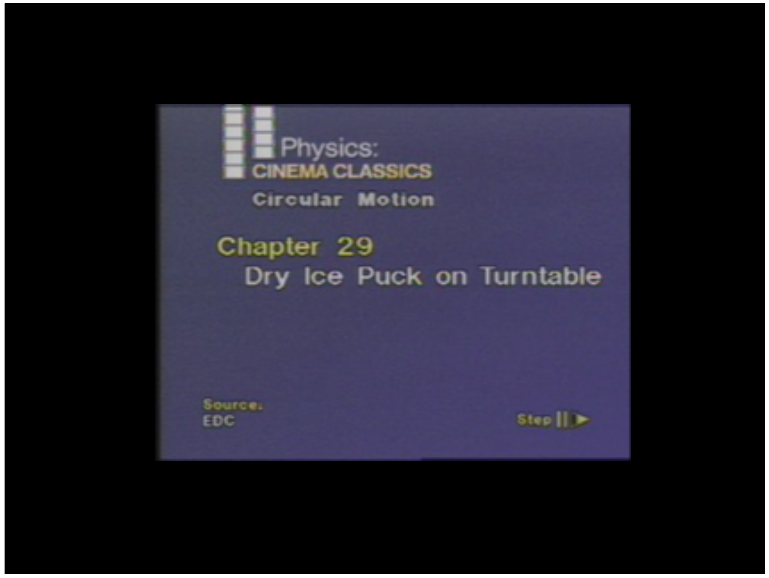
Forces Acting on the Air

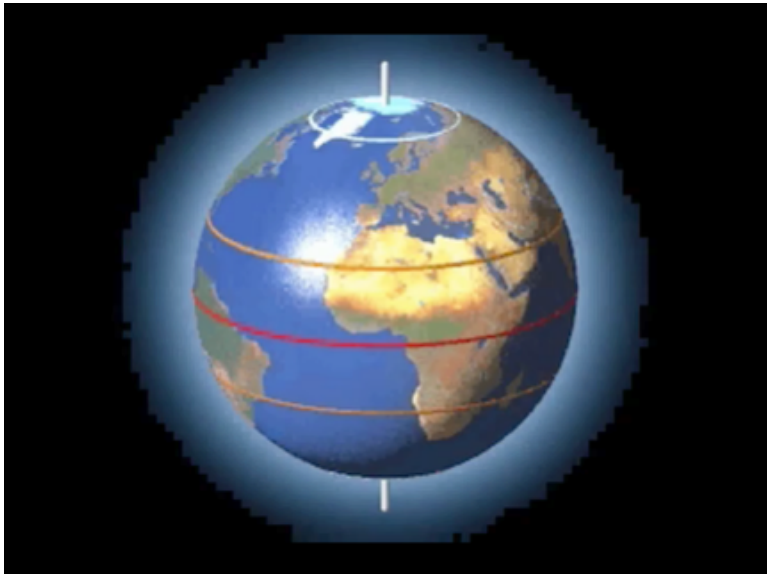
- Pressure gradient force (pushing)
- Gravity (falling)
- Friction (rubbing against the surface)
- "Apparent" forces
  - The Coriolis Force
  - Centrifugal Force

If Earth didn't rotate

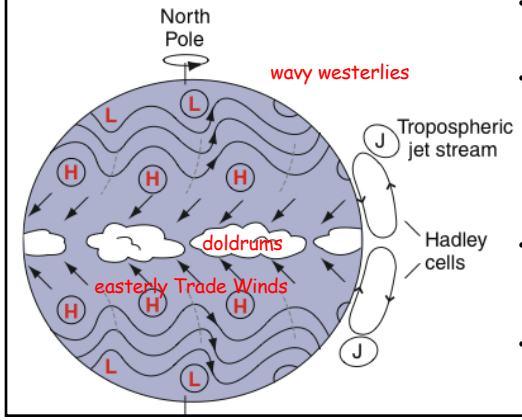
- It would be easy to balance radiation at each latitude
- Thermal convection would form an overturning cell in each hemisphere
- Energy transport from equator upward and toward both poles
- Surface wind in the USA would always blow from the North!



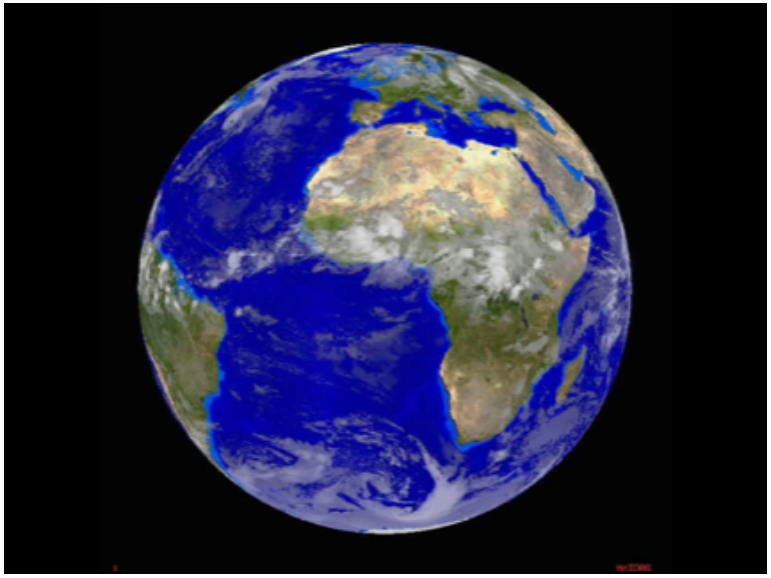




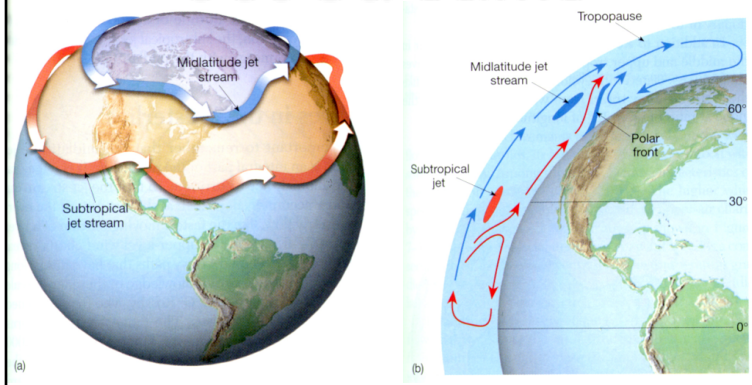
Wind Patterns on the Rotating Earth



- Thermally direct convective cells only in the 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



Jet Streams

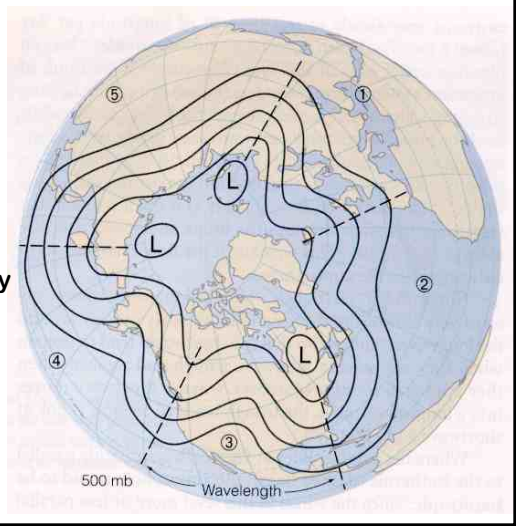


Westerly winds outside the tropics are polar vortices that conserve angular momentum of the planet as air flows toward the axis of rotation

Waves on the polar vortex

Westerlies typically organized into 4-6 "long waves"

Wind blows through them, but waves themselves propagate slowly

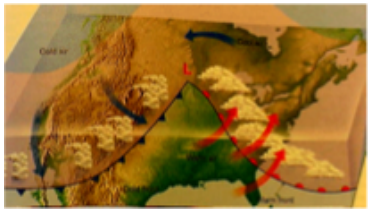


Midlatitude Cyclones

Equator-to-pole temperature gradient tilts pressure surfaces and produces westerly jets in midlatitudes

Waves in the jet induce divergence and convergence aloft, leading to surface highs and lows

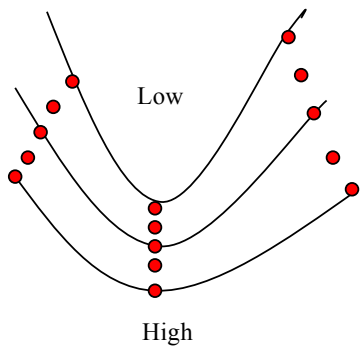
Surface circulations amplify the wave by transporting heat to the north and south around the surface low



Resulting "cyclones" are crucial to the transport of energy through the middle latitudes

Lowers center of mass of atmosphere

Convergence and Divergence

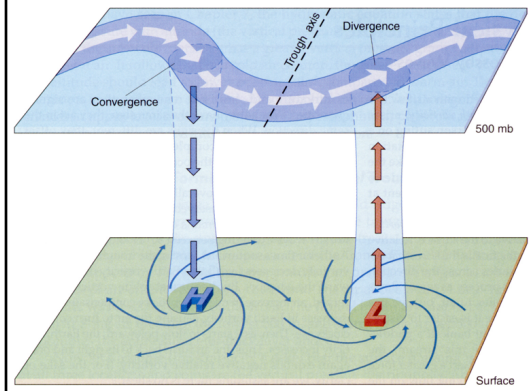


High above the surface

"Cyclogenesis"

When upper-level **divergence** is stronger than lower-level **convergence**, more air is taken out at the top than is brought in at the bottom. Surface **pressure drops**, and the **low intensifies**, or "deepens."

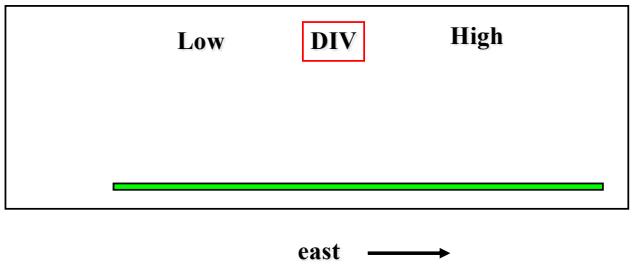
Divergence, Spin, and Tilt



- Maximum upper level convergence and divergence are *between* ridges and troughs
- Phase of developing wave "tilts" to the west with height

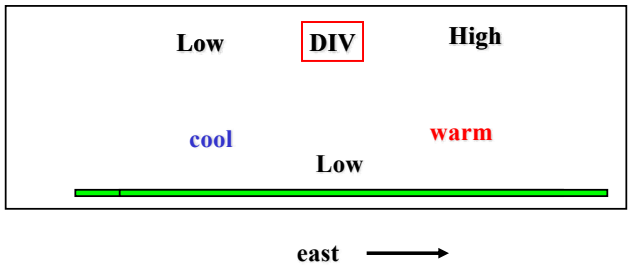
Before the Storm

- Vertical cross-section looking North
- Imagine a jet-stream wiggle passes overhead
- Diverging air aloft … less mass above the middle!
- Pressure drops



Birth of a Storm

- Surface winds respond to surface pressure gradient … transport cold air southward behind the low and warm air northward ahead of low
- This amplifies the upper level trough and ridge
- Enhances upper-level divergence …



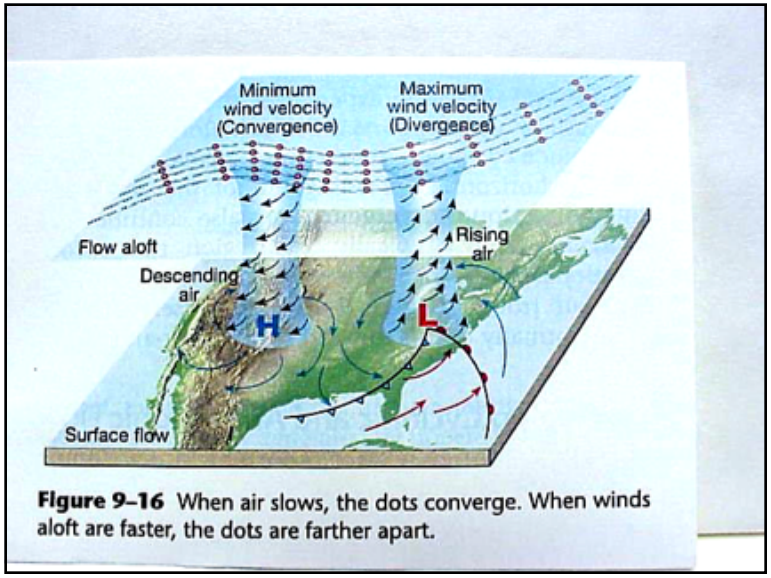
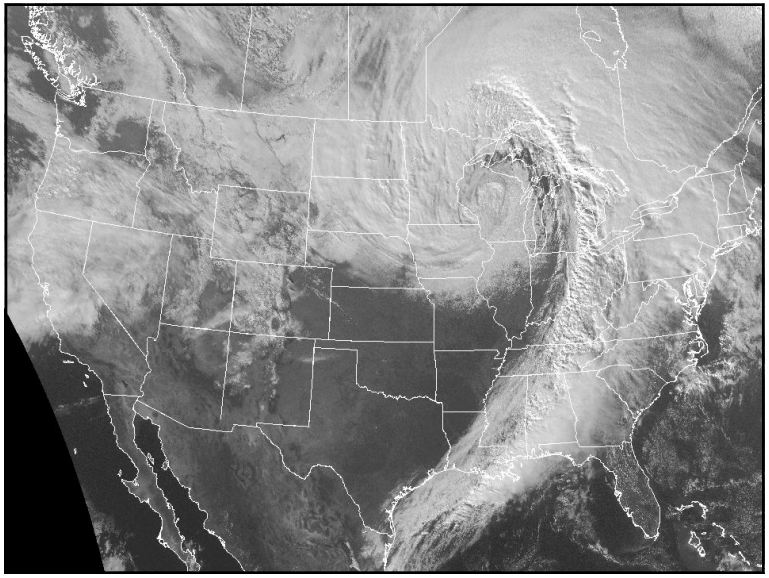


Figure 9–16 When air slows, the dots converge. When winds aloft are faster, the dots are farther apart.



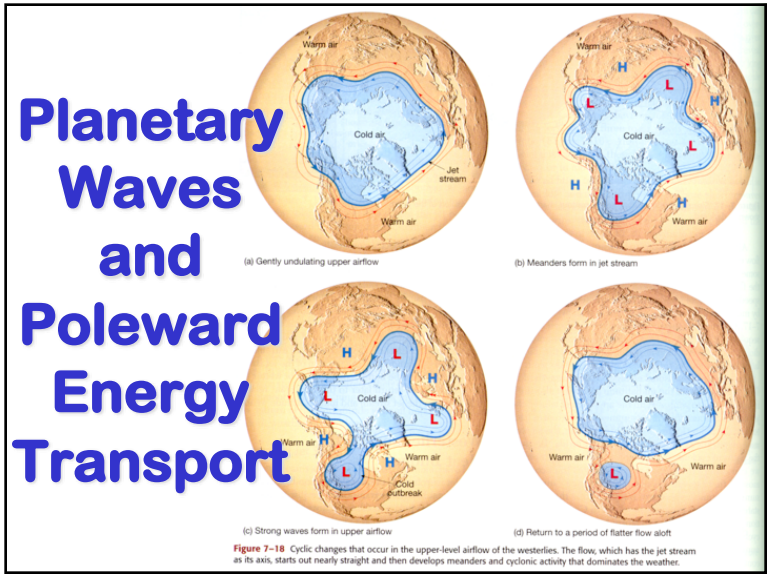
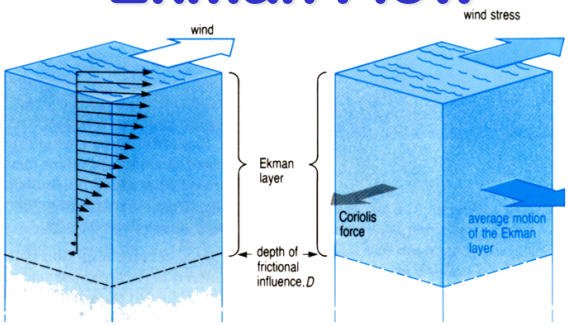


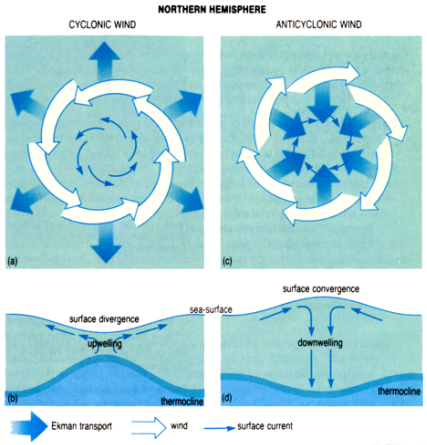
Figure 7–18 Cyclic changes that occur in the upper-level airflow of the westerlies. The flow, which has the jet stream as its axis, starts out nearly straight and then develops meanders and cyclonic activity that dominates the weather.

Ekman Flow



- Combined effects of Coriolis and friction on "stack" of thin layers
- Each layer moves more slowly and further right than layer above ("spiral")
- Average motion is 90° *to right* of wind

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

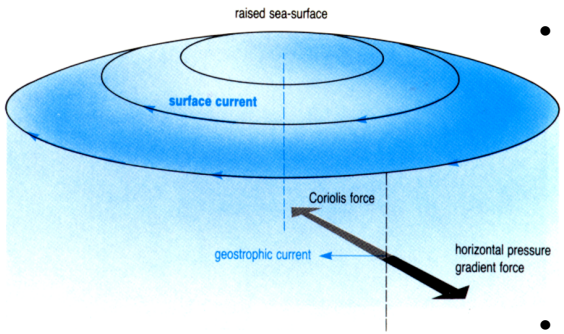
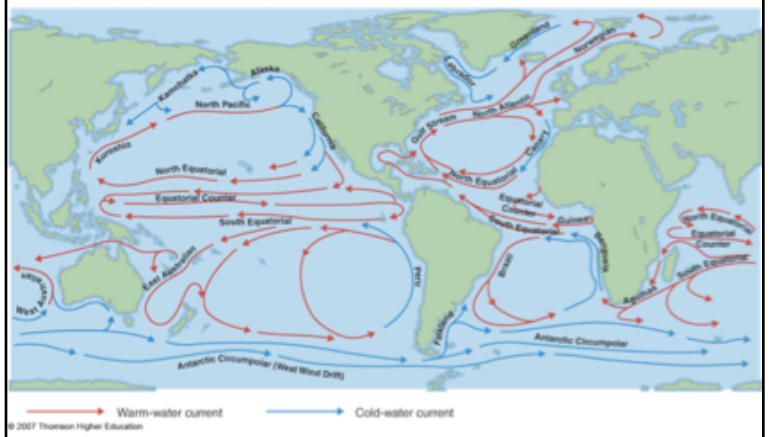


Figure 3.24 The generation of geostrophic current flow in a gyre driven by anticyclonic winds in the Northern Hemisphere. This current is driven by the wind only indirectly and persists below the wind-driven (Ekman) layer.

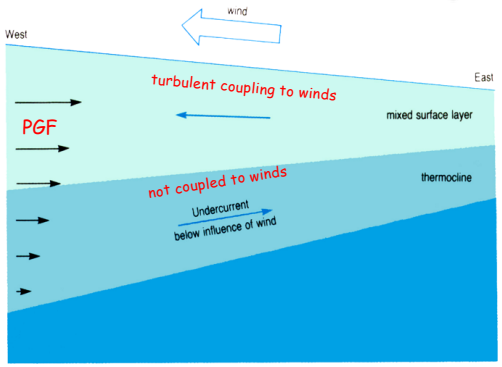
- Convergence of Ekman flow raises sea surface
- Rotating "dome" results

Ocean Surface Currents



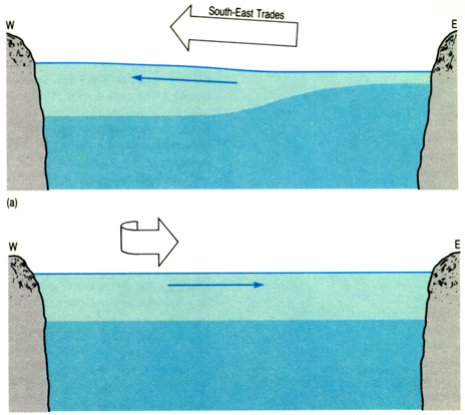
Warm flows toward poles, cold toward

Cross-Section at Equator



- 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

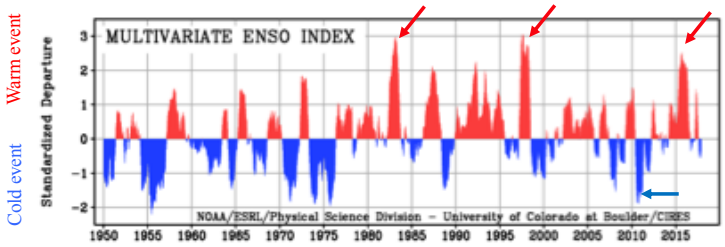
El Niño



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

El Niño Southern Oscillation (ENSO)

- Southern Oscillation 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"
- Negative SOI anomaly: "La Niña"



Thermohaline Circulation