Global and Synoptic Scale Circulation Systems

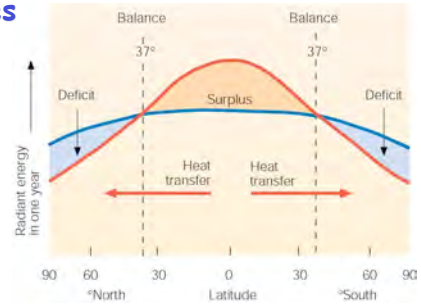
Poleward energy transport on a rotating sphere

Hadley cells and Ferrel cells

Polar vortex and midlatitude jet streams

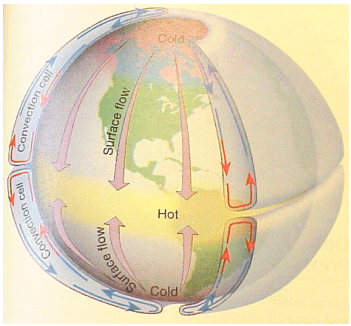
Midlatitude cyclones as waves

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

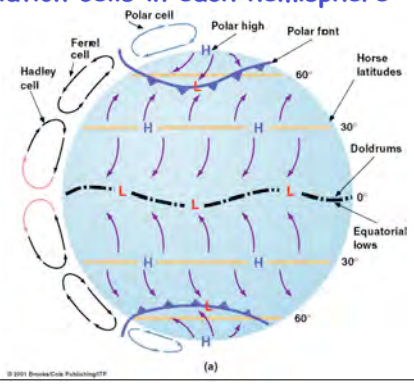


If the Earth didn't rotate, it would be easy for the flow of air to balance the energy

- Thermal convection leads to formation of convection cell in each hemisphere
- Energy transported from equator toward poles
- What would prevailing wind direction be over N. America with this flow pattern on a rotating earth?



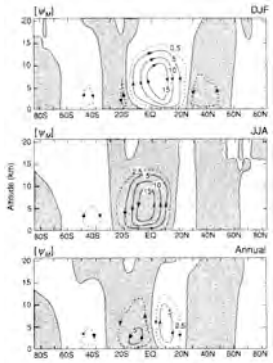
Wind patterns on a rotating Earth
3 circulation cells in each hemisphere



Key features of three cell model

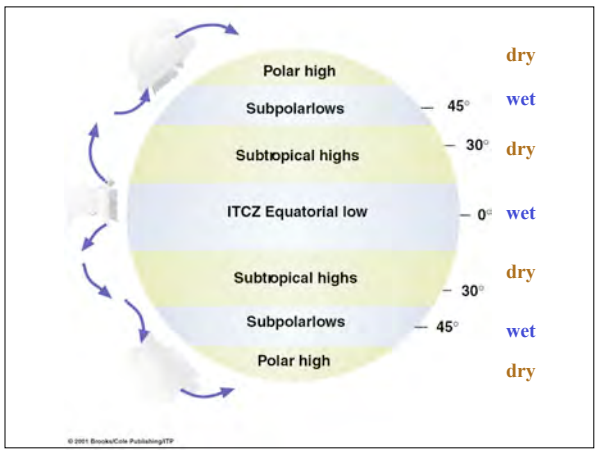
- **Hadley cell** (thermally direct cell)
  - driven by *N-S gradient in heating*
  - air *rises near equator and descends* near 30 degrees
  - explains deserts; trade winds; ITCZ
- **Ferrel Cell** (indirect thermal cell)
  - driven by heat transports of *eddies*
  - air *rises near 60 degrees* and descends 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

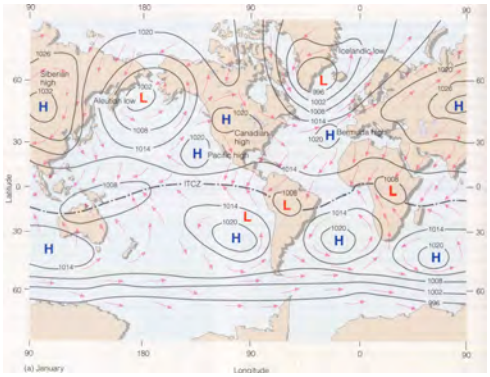


Mean meridional mass streamfunction (10^{10} kg s^{-1})

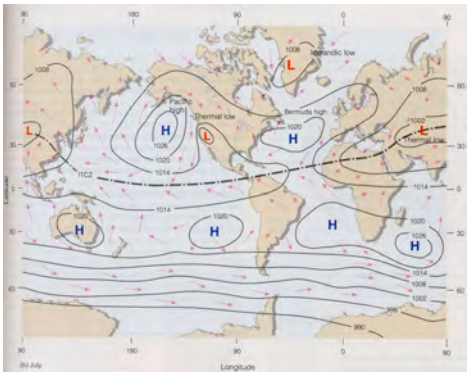
- Strongest feature is the Hadley Cell
  - Rising air in tropics
  - Poleward flow aloft into winter hemisphere
  - Sinking air in winter subtropics
  - Surface flow equatorward
  - Rising branch slightly displaced into summer hemisphere
- Much weaker Ferrel Cells in middle latitudes
  - "Thermally indirect"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



General Circulation - January

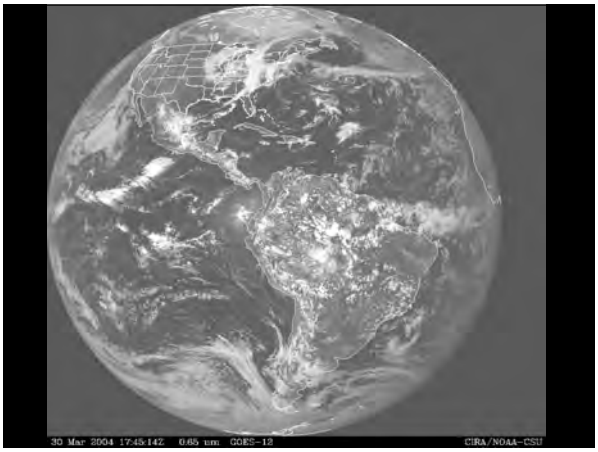


General Circulation - July



Understanding the General 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 fluid rises and moves poleward. Equator-to-pole Hadley cell is impossible in the presence of rotation
3. In the Northern Hemisphere, a fluid 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!



Jargon Break!

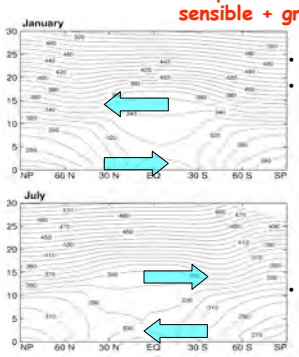
- "Zonal" means "east-west"
- "Meridional" means "north-south" (along meridians)
- MMC is the "Mean Meridional Circulation" … zonally-averaged cross section of air flow

Energy in the Global Atmosphere

Name	Symbol	Formula	Amount $\times 10^6$ 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 … $c_v T + gz$ account for 97%
- KE 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

"Moist Static Energy"
$h = c_p T + gz + Lq$
sensible + gravitational + latent



ECMWF Analyses

- Increases upward aloft (O_3)
- Decreases upward near surface in tropics and in midlatitude summer
  - Near surface, upward decrease of Lq dominates
  - Above midtroposphere, q is negligible … upward increase in $c_p T+gz$ dominates
  - Moist static energy must have a mid-tropospheric minimum
- Export from tropics requires upward transport in protected cores

Idealized Hadley Circulation

- Heat source at the surface and in the tropics (R_{net}, precip)
- Heat sink aloft and at the poles (OLR)
- Elevated pressure surfaces in the tropics
- Thermally direct cell transports heat from sources to sinks

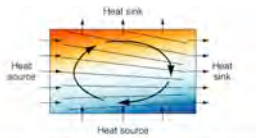
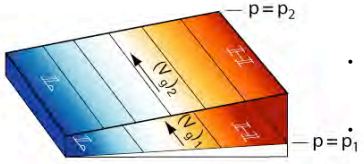


Fig. 7.23 Vertical cross section through a steady-state circulation in the laboratory, driven by the distribution of heat sources and heat sinks as indicated. The colored shading indicates the distribution of temperature and density, with cooler, denser fluid represented by blue. The sloping black lines represent pressure surfaces. Note that the flow is directed down the horizontal pressure gradient at both upper and lower levels.

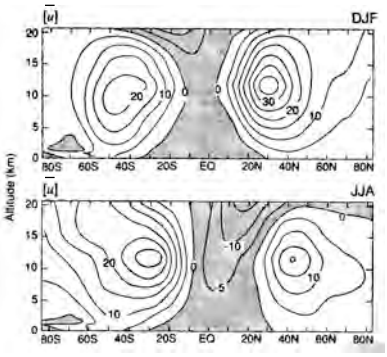
Thermal Wind Balance Produces Jets



- 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

Mean Zonal Wind



Time mean zonal mean zonal wind component (m/s)

- Midlatitude westerly winds
- Deep tropical easterlies
- Well-defined winter wind max ~ 30° lat at ~ 12 km ("jet stream")
- Summer jet is weaker and further poleward

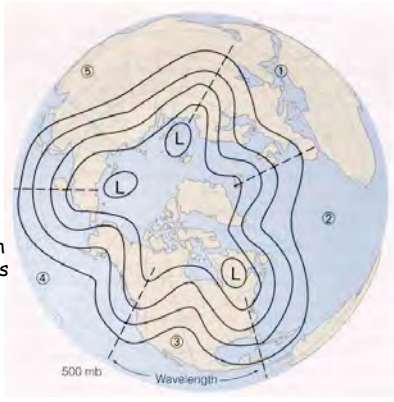
Extratropical storms are Eddies in the Jet Stream

- 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.

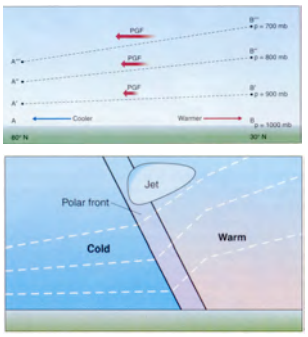
Waves on the polar vortex

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

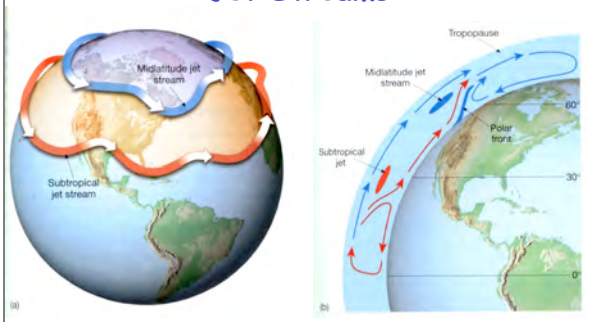


Baroclinicity and the Polar Front Jet



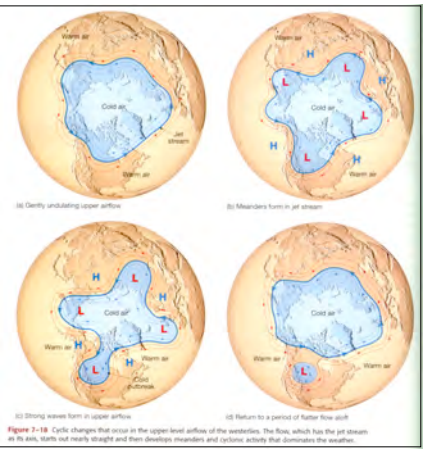
- Air density depends on temperature
- Warm air occupies more vertical space per mass (pressure depth)
- Tilt of pressure surfaces increases with height
- Coriolis force produces wind flow into screen
- Wind max (jet stream) occurs above steepest temperature gradient

Jet Streams

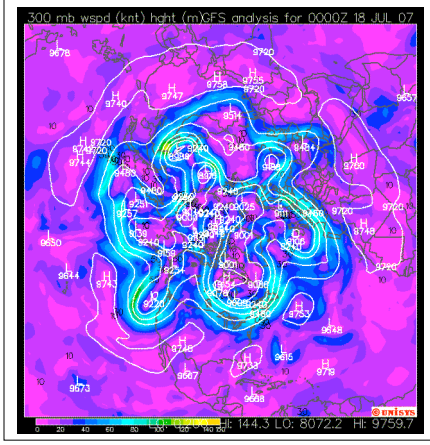


- Subtropical Jet is zonal mean response to poleward flow in upper branch of Hadley Cell
- Polar front jet is response to meridional temperature gradients

Planetary Waves and Poleward Energy Transport

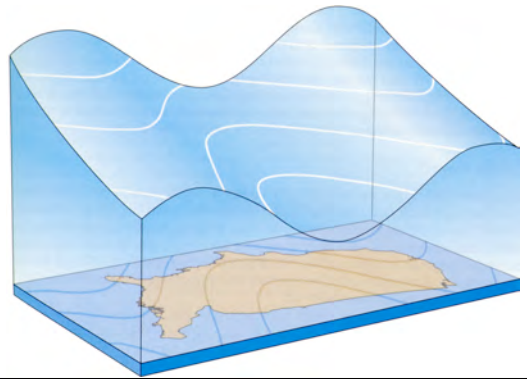


Today @ 300 mb

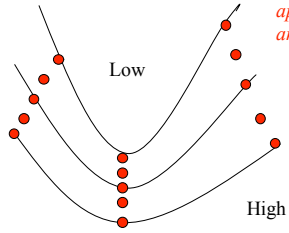


- "Bowl-shaped" height contours
- Waves
- Huge ridge over CO!
- Jets

Developing Transient Wave



Convergence and Divergence



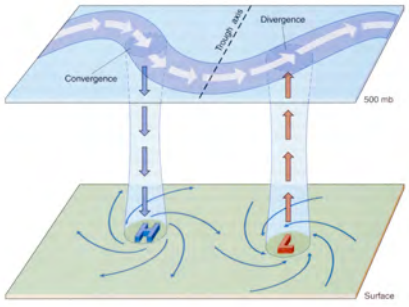
500 mb height

Winds slow down and converge approaching a trough … speed up and diverge approaching a ridge

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, Vorticity, and Tilt

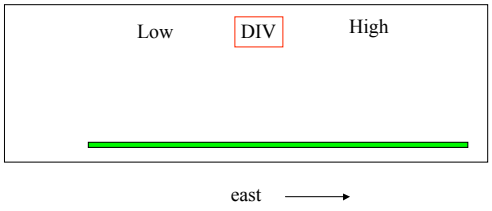


- Maximum upper level convergence and divergence are *between* ridges and troughs
- Phase of developing wave "tilts" to the west with height

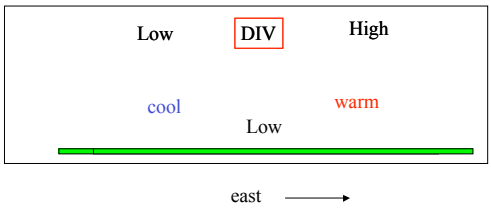
Cyclone development:

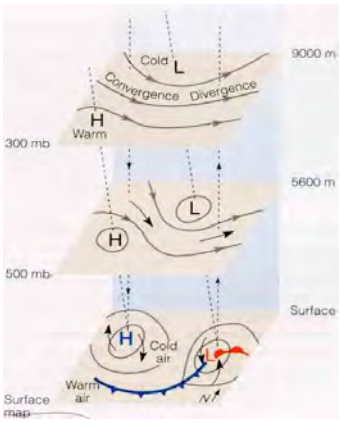
- baroclinic instability (baroclinic means temperature varies on an isobaric surface) causes initial 'perturbation' to grow.
- occurs in the presence of strong temperature gradients.

Imagine a short wave trough passes overhead (*looking North*): Where will surface low develop?



(*looking North*):
Near the surface, where will we have cold and warm advection?
Will this amplify or weaken the upper level low?
How about the upper level divergence?
Will a more intense upper level low strengthen or weaken the surface low?



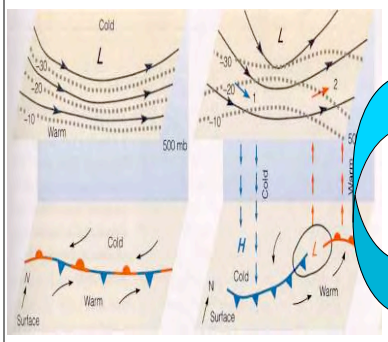


Vertical structure of a midlatitude cyclone

Upper level low is ***tilted westward with height*** with respect to the surface.

UPPER LEVEL DIVERGENCE INITIATES AND MAINTAINS A SURFACE LOW.

Baroclinic Instability

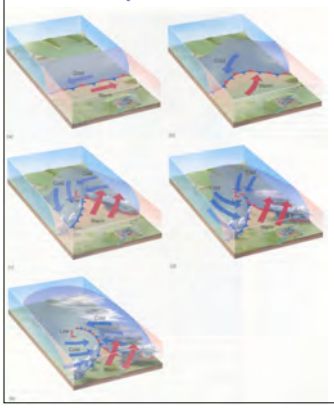


- Upper level shortwave passes
- Upper level divergence -> sfc low
- Cold advection throughout lower troposphere
- Cold advection intensifies upper low

Leads to more upper level divergence

Temperature advection is key!

Lifecycle of a Midlatitude Cyclone



- Pressure surfaces tilt because of N-S temperature contrast
- Passing wave initiates divergence and cyclonic vorticity
- Cold air undercuts warm, and flows south
- Cold air advection undermines upper trough, deepening it
- N-S mixing in cyclone eventually consumes the available potential energy, and cyclone dies

Summary of Cyclone Weather

Roles of convergence and divergence aloft

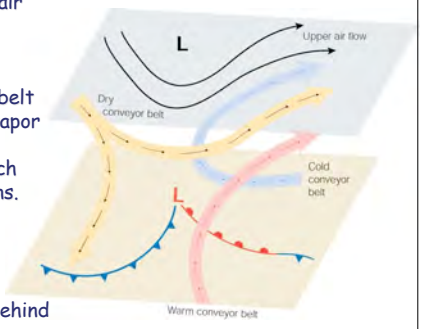
Pattern of clouds, precipitation, and temperatures on the ground

Conveyor Belt Model

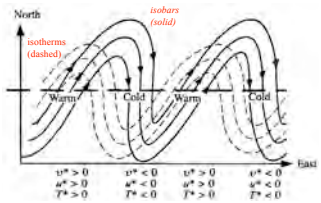
This model describes rising and sinking air along three "conveyor belts"

A warm conveyor belt rises with water vapor above the cold conveyor belt which also rises and turns.

Finally the dry conveyor belt descends bringing clearer weather behind the storm.



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

Northward Heat Flux

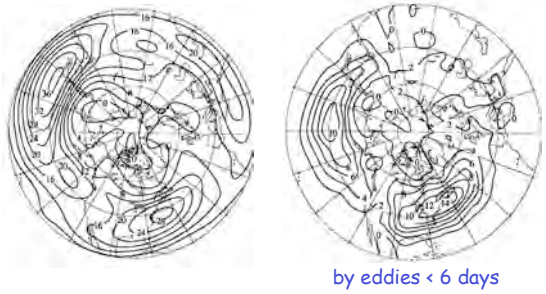
$$[\overline{vT}] = [\overline{v}][\overline{T}] + [\overline{v^*T^*}] + [\overline{v'T'}]$$

total MMC "stationary eddies" "transients"

- Mean of product is decomposed and rules of averaging are applied, leaving product of means plus means of products of two kinds of perturbations
- Mean of products is heat flux associated with MMC (Hadley and Ferrel Cells)
- Heat flux by stationary eddies is associated with large-scale features produced by land-sea contrasts and topography that don't move around
- "Transients" are traveling weather disturbances (waves and fronts), which move a lot of heat!

Heat Transport by Transient Eddies

500 mb wind speed (DJF) 850 mb Heat Transport



by eddies < 6 days

Very strong influence of "storm track" regions associated with air-sea temperature contrasts

Stationary Eddies (Waves)

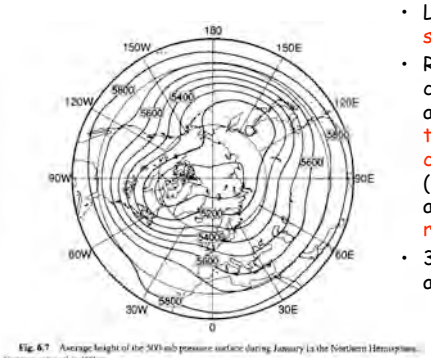
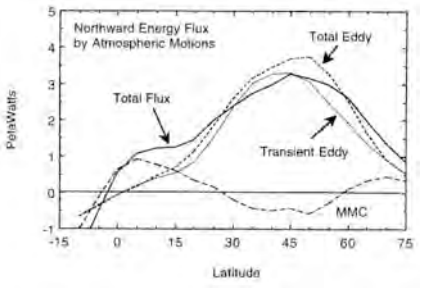


Fig. 6.7 Average height of the 500-mb pressure surface during January in the Northern Hemisphere. Contour interval is 100 m.

- Like a big spinning bowl
- Ridges and creases in bowl are caused by temperature contrasts (land vs ocean) and by mountain ranges
- 3 or 4 waves are typical

Poleward Energy Transport



- MMC carries energy out of tropics (as gz)
- Eddy motions carry it the rest of the way (mostly as transients)
- Consider $d/d\varphi$ of energy flux (divergence)
- Thermally indirect MMC in midlats is response to strong eddy flux divergences

Global Energy Cascade

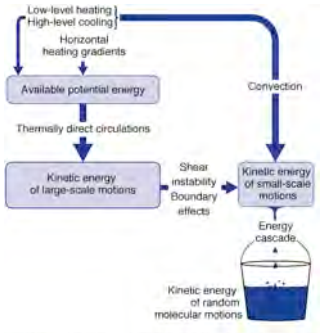


Fig. 7.24 Schematic flow diagram for the kinetic energy cycle in the atmospheric general circulation.

- Heterogeneous heating creates available potential energy (APE)
- Thermally-direct MMC converts APE to zonal mean KE
- Baroclinic instability converts zonal mean KE to eddy KE
- Eddies shed eddies "and so on to viscosity"
- Dissipation of KE converts energy back to heat

The "Big Picture"

- We've emphasized horizontal transport of energy to balance the planetary energy budget:
  - Hadley Cell
  - Subtropical divergence
  - Midlatitude cyclones and conveyor belts
- What about vertical motion?
  - "Up-warm, down cold"
  - "Up moist, down-dry"
- Severe weather is all about vertical motion, and represents local release of energy that contributes to planetary energy balance

Stuff to Remember

- 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
- The resulting polar vortex is unstable, producing waves in the jets that allow mixing across the midlatitudes
  (and which also control winter weather!)