Wednesday AM, Explain: Winds

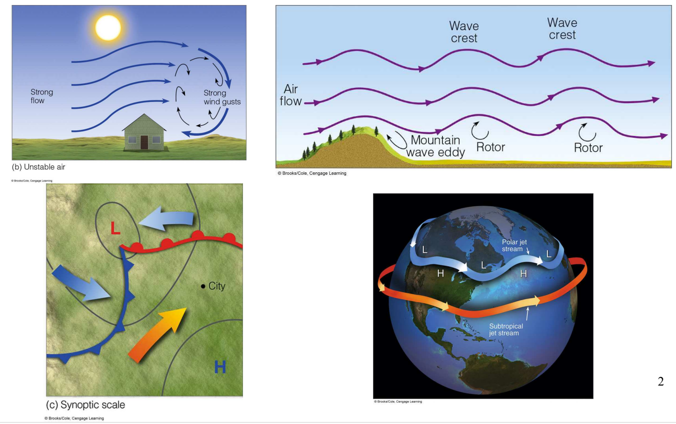
WEDNESDAY: global weather and climate

## Forces & Moving Air

- What makes the wind blow?
- Why do winds blow counterclockwise around lows and clockwise around highs?
- General circulation of the atmosphere

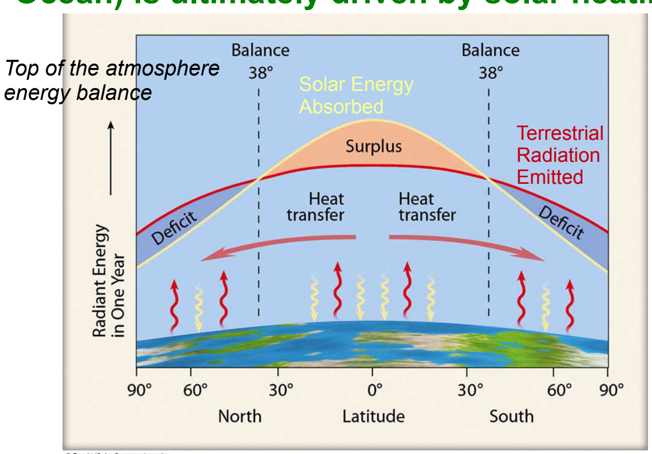


## Atmospheric Motion takes Place on a Variety of Scales






## The Circulation of the Atmosphere (and the Ocean) is ultimately driven by solar heating.

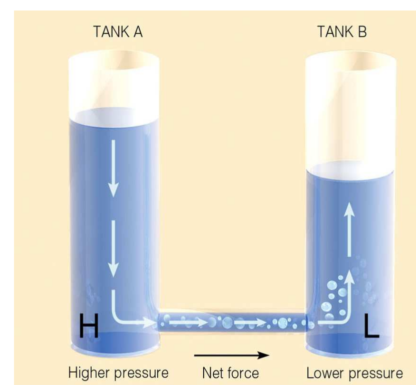







## Motion due to Pressure Differences

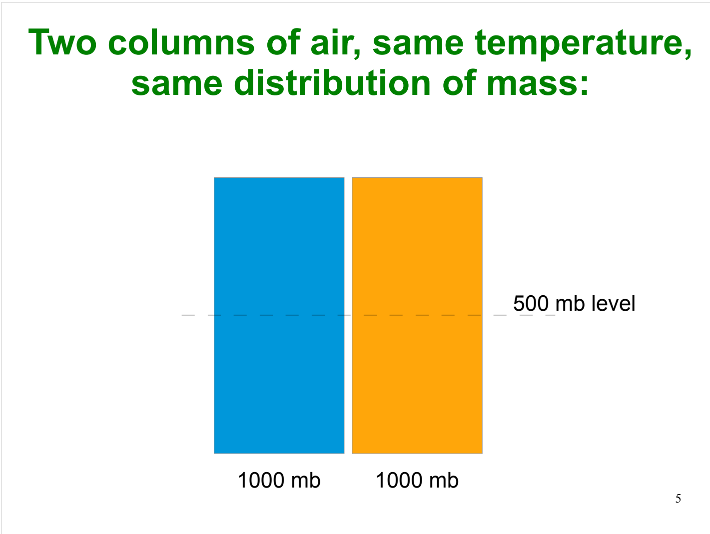
- Two tanks filled with water, tank A has more water than tank B
- The pressure at the bottom (the weight of the water above) is higher in tank A than in tank B
- This pressure difference forces the water to flow from tank A into tank B (high to low pressure)

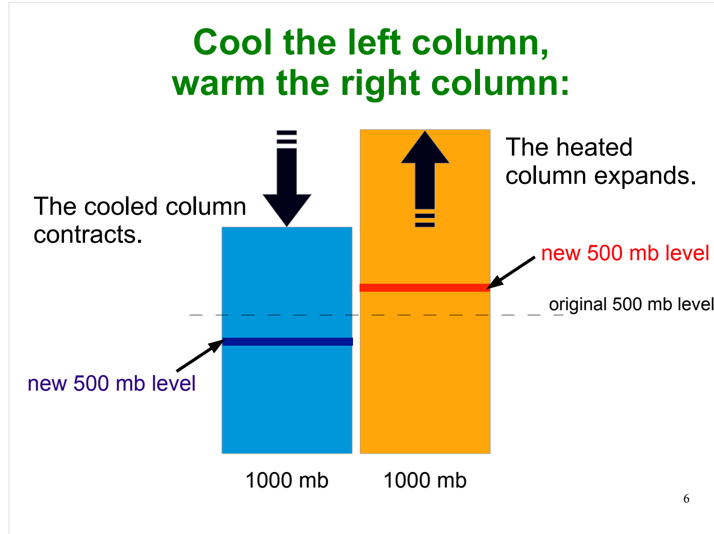


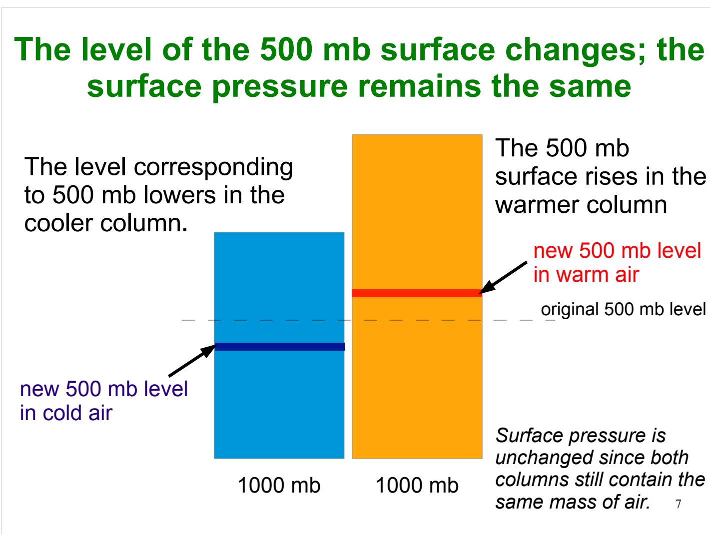


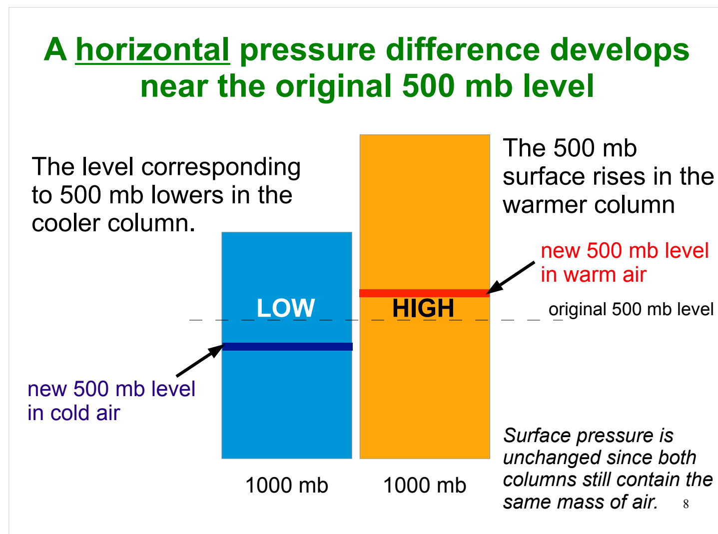



Thomas Birner, ATS, CSU


Two columns of air, same temperature, same distribution of mass:
500 mb level
1000 mb
1000 mb
5


Cool the left column, warm the right column:
The cooled column contracts.
The heated column expands.
new 500 mb level
original 500 mb level
new 500 mb level
1000 mb
1000 mb
6


The level of the 500 mb surface changes; the surface pressure remains the same
The level corresponding to 500 mb lowers in the cooler column.
The 500 mb surface rises in the warmer column
new 500 mb level in warm air
original 500 mb level
new 500 mb level in cold air
Surface pressure is unchanged since both columns still contain the same mass of air.
1000 mb
1000 mb
7


A horizontal pressure difference develops near the original 500 mb level
The level corresponding to 500 mb lowers in the cooler column.
The 500 mb surface rises in the warmer column
new 500 mb level in warm air
LOW
HIGH
original 500 mb level
new 500 mb level in cold air
Surface pressure is unchanged since both columns still contain the same mass of air.
1000 mb
1000 mb
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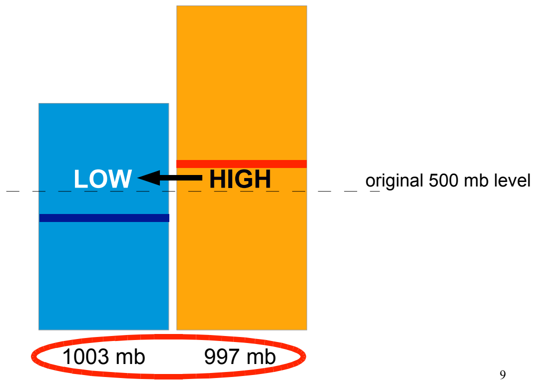
## Air moves from high to low pressure in the middle of the column, eventually causing the surface pressure to change

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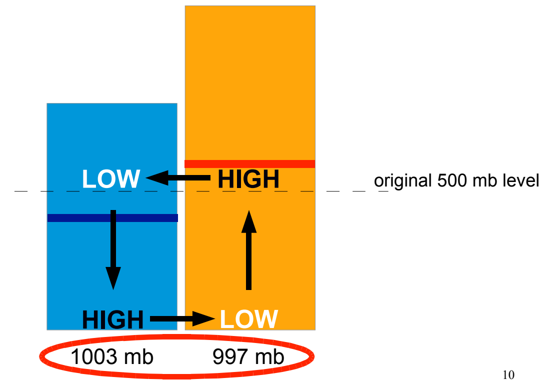


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# What have we just observed?

- Starting with 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 along a horizontal surface
- The pressure differences then induced flow in the fluid (air)
- This is a microcosm of how the atmosphere converts heating into motion (i.e. Wind!)

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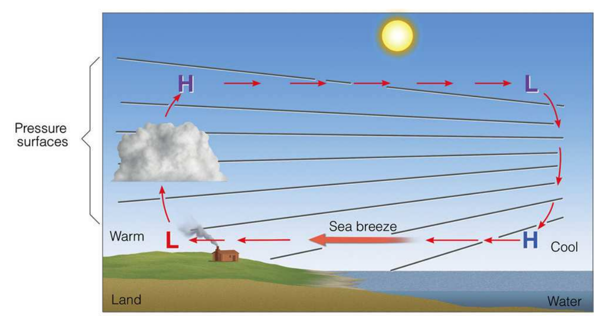
# Example: Sea Breeze

- During the day, land warms up more strongly than a nearby ocean → rising motion (cloud formation possible) and outward flow at upper levels → inward flow (sea breeze) at low levels to replace ascended air over land




(a) Sea breeze



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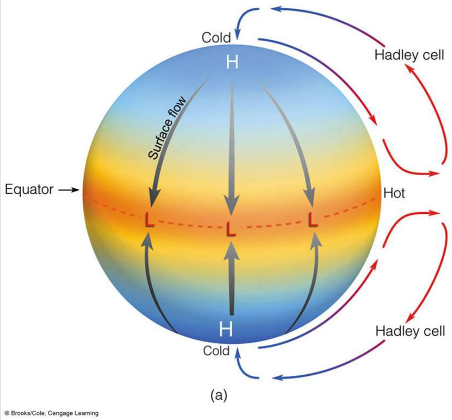
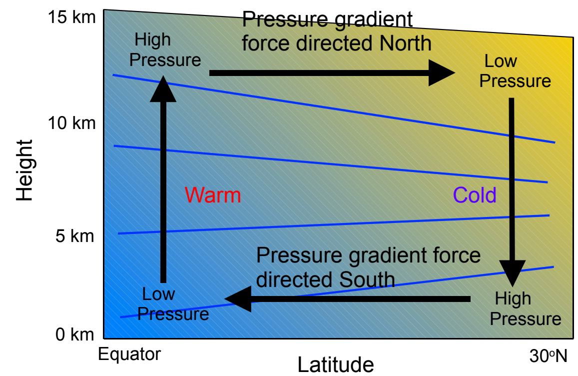
## Single (Hadley) Cell: non-rotating Earth




- Differential heating of tropics vs poles
- Circulation somewhat like sea breeze, except globally
- Energy (heat) transported from equator to poles
- Air rises at the equator and sinks at the poles



## Thermally direct Hadley Cell




Differential heating between tropics and higher latitudes drives thermal circulation.



## Forces and Winds

- Pressure gradients produce air movement/flow: why doesn't the wind blow from high to low pressure?
- Various other forces act simultaneously to cause the wind speed and direction to differ from that produced by the pressure gradient
- Newton's laws of motion describe the relationship between forces and motion:
  - **1st Law:** an object at rest will stay at rest and an object will remain in motion (and travel at constant speed along a straight line) as long as no force is exerted on the object
  - **2nd Law:** the force exerted on an object equals its mass times the acceleration produced: F = ma



## Air accelerates in the presence of a force (a = F/m)

## Forces controlling the wind

- Pressure Gradient Force
- Coriolis Force
- Centrifugal Force
- Friction

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- Coriolis and Centrifugal are "*apparent*" forces, i.e. they only *apparently* exist because of our specific choice of a rotating coordinate system

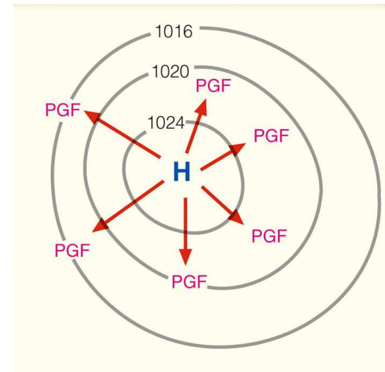
## Forces expressed as Vectors

- Forces have two properties:
  - Magnitude or Size
  - Direction
- Vectors have those same two properties:
  - Length of arrow denotes magnitude
  - Direction of arrow denotes direction



## Pressure Gradient Force

- Magnitude
  - Inversely proportional to the distance between isobars (contour lines) – the closer together the stronger the force
- Direction
  - Always directed towards lower pressure

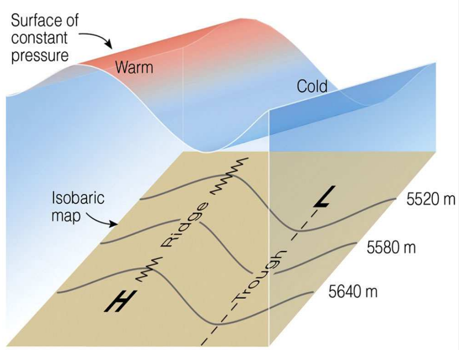





## Troughs and Ridges

- Temperature gradients generally produce pressure gradients
- Isobars (lines of constant pressure) usually decrease from equator to pole (south to north in our hemisphere)

- But contour lines are usually not straight:
  - Ridges (elongated highs) occur where air is relatively warm
  - Troughs (elongated lows) occur where air is relatively cold

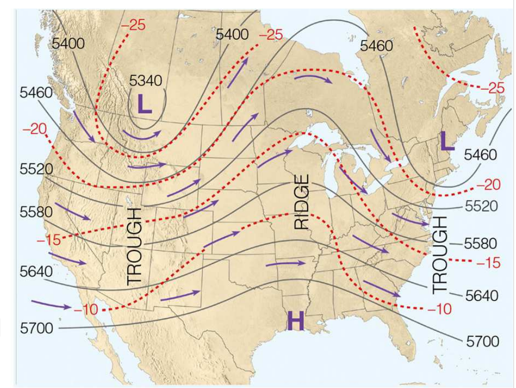





## Pressure / height patterns & winds aloft

At upper levels, winds blow parallel to the pressure/height contours.

Winds are deflected counterclockwise around lows and clockwise around highs.

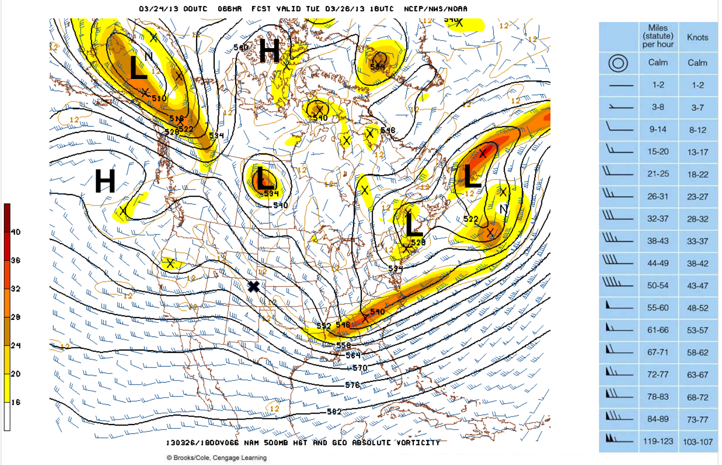



(b) Upper-air map (500 mb)



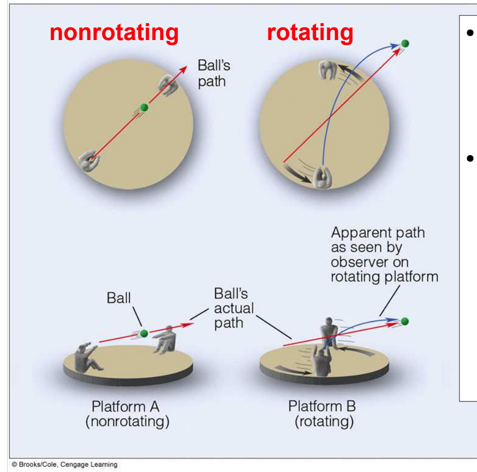
*This is northern hemisphere!*

## Pressure / height patterns (500 mb) & winds aloft: Example






## Coriolis Force






- Ball is going in a straight line for both the nonrotating and rotating case!
- Viewed from the observer on the rotating platform (inside the rotating coordinate system) the ball is deflected to the right by an apparent force – the Coriolis force

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## Coriolis Force

- Magnitude
  - Depends on the latitude and the speed of movement of the air parcel
    - The higher the latitude, the stronger the Coriolis force (zero at the equator, maximum at the poles)
    - The faster the speed, the stronger 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

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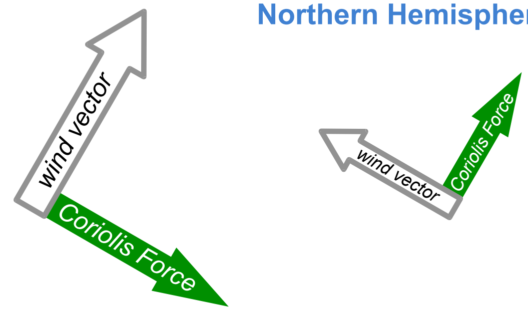
## Northern Hemisphere (NH)




- Magnitude
  - The faster the speed, the stronger the Coriolis force
- Direction
  - The Coriolis force *always* acts at right angles to the direction of movement
    - To the right in the northern hemisphere

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## Coriolis Deflections (<u>NH</u>)

- 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

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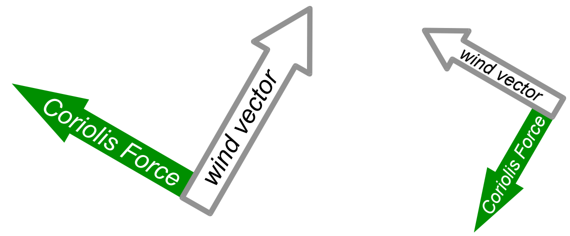
## Southern Hemisphere (SH)




- Magnitude
  - The faster the speed, the stronger the Coriolis force
- Direction
  - The Coriolis force *always* acts at right angles to the direction of movement
    - <u>To the left in the southern hemisphere</u>

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### Gaspard-Gustave Coriolis (1792–1843)

- French mathematician, mechanical engineer
- Coined term “work” (= force acting through a distance)
- One of the first to formulate correct expression for kinetic energy ($\frac{1}{2}mv^2$)
- His work on (apparent) forces in rotating systems did not address any atmospheric science problems
- Contemporary scientists working on atmospheric problems were not aware of his work on rotating systems

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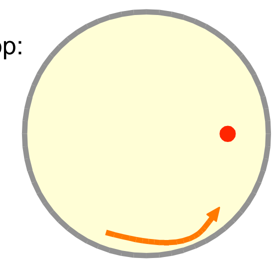
## Coriolis Force: Rotating Table Demonstration

View from the top:



View from the side:

Gravity = Centripetal Force

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## Coriolis Force – Angular Momentum Perspective

- Angular Momentum ~ Rotational Momentum
  - is conserved (does not change), unless rotational forces (torques) are acting (e.g. friction, or your legs pushing the pedals of your bike)
  - for the same angular momentum, the closer to the axis of rotation the faster you rotate – this is why a figure skater pulling her arms in will spin up
- On the rotating Earth, moving closer to the poles means moving closer to the axis of rotation – as with the figure skater this results in spin up → deflection to the right in the NH, deflection to the left in the SH
- Likewise, moving eastward (in the direction of rotation) equals a spin up on the rotating planet – this has to be compensated by moving farther away from the axis of rotation → deflection to the right/left in the NH/SH

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## Coriolis Force – Angular Momentum Perspective

- Angular Momentum ~ Rotational Momentum
  - is conserved (does not change), unless rotational forces (torques) are acting (e.g. friction, or your legs pushing the pedals of your bike)
  - for the same angular momentum, the closer to the axis of rotation the faster you rotate – this is why a figure skater pulling her arms in will spin up
- Moving farther away from the poles means moving farther away from the axis of rotation – as with the figure skater this results in slow down → deflection to the right in the NH, deflection to the left in the SH
- Likewise, moving westward (against the direction of rotation) equals a slow down on the rotating planet – this has to be compensated by moving closer to the axis of rotation → deflection to the right/left in the NH/SH

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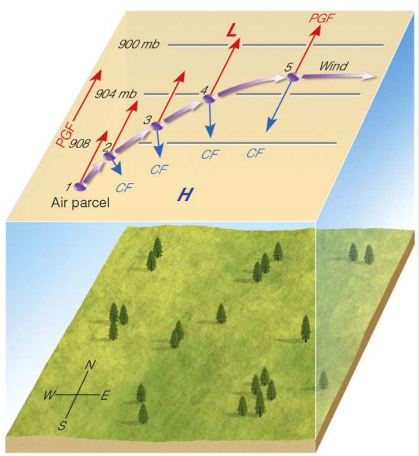
## Coriolis Force & Geostrophic Wind

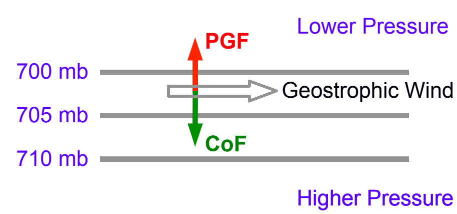
- Coriolis force acts to the right in the northern hemisphere and is stronger for higher wind speed
- Pressure gradient points from high to low pressure
- When Coriolis and pressure gradient force balance → no net force and wind is on a straight line with constant speed





## Geostrophic Wind

- Geostrophic Wind = Flow in which the pressure gradient force balances the Coriolis force → flow along lines of constant pressure (isobars)
- often a good approximation at upper levels (e.g. 500 mb)

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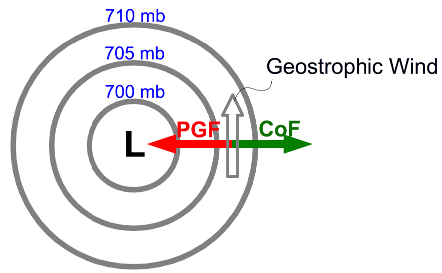


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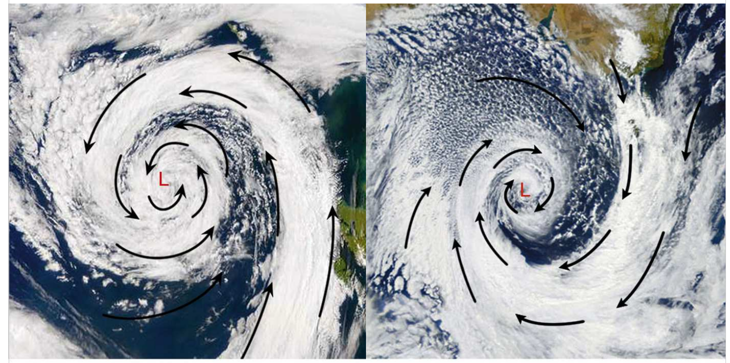
## Remark about Hemispheric Difference

Coriolis acts to the right in the Northern Hemisphere → counterclockwise flow around lows; in the Southern Hemisphere Coriolis acts to the left → clockwise flow around lows. Vice versa for highs.

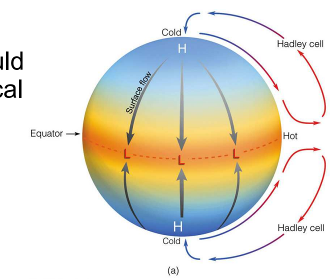



(a) Northern Hemisphere **counterclockwise** (b) Southern Hemisphere **clockwise**



## What's wrong with the single cell model of the general circulation?

- Neglect of rotation, but the Earth does rotate:
  - with rotation comes Coriolis force
  - Surface winds in single cell model would tend to spin down the Earth
  - Upper level winds would accelerate to unphysical speeds near the poles



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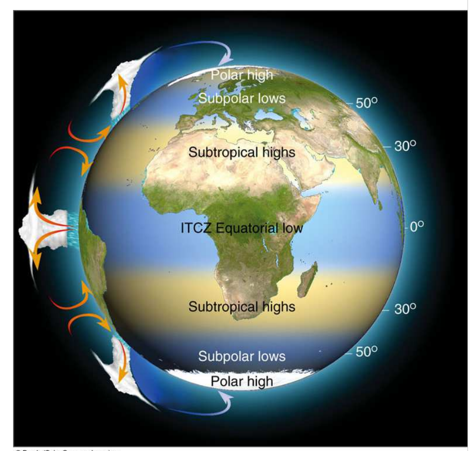
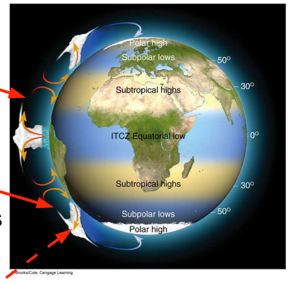
## Three Cell Model: rotating Earth

- Rising motion (deep convection, lots of rain) in tropics
- Sinking motion (adiabatic warming & drying) in subtropics
- Atmospheric storm formation in midlatitudes along polar front



## Key Features of the Three Cell Model




- **Hadley Cell** (thermally direct)
  - driven by N–S gradient in heating
  - air rises near equator and sinks near 30 degrees
  - → deserts, trade winds, ITCZ
- **Ferrel Cell** (thermally indirect)
  - driven by heat transport of eddies
  - air rises near 60 degrees and sinks near 30 degrees
  - Explains midlatitude surface westerlies (30–60 degrees)
- Weak winds found near the equator and 30 degrees
- Boundary between cold polar air and midlatitude warmer air is the polar front

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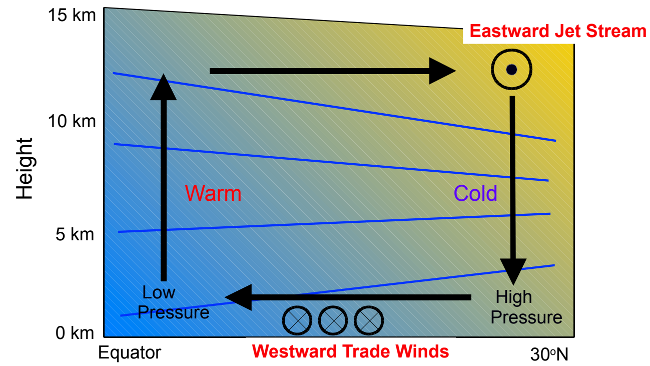
## Thermally direct Hadley Cell




The Coriolis force deflects flow to the right (N.H.) setting up the Jet Stream and Trade Winds. Strength depends on pressure gradient, i.e. on temperature contrast between tropics and higher latitudes.

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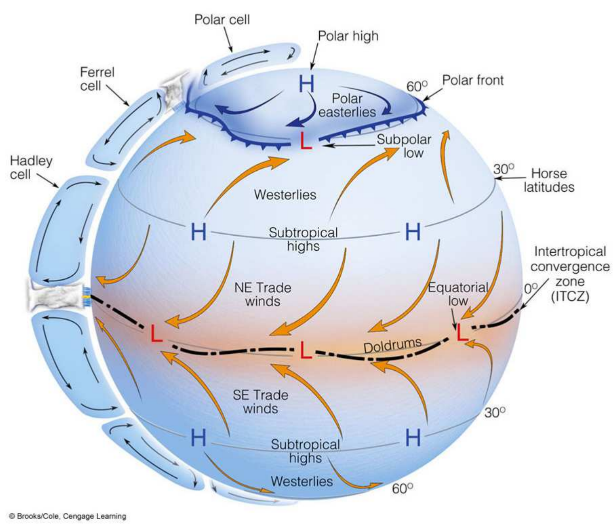


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## The Role of Midlatitude Storms (Eddies)

- (Angular/rotational) momentum is transferred from the Earth to the atmosphere in the trade wind belt.
- (Angular/rotational) momentum is transferred from the atmosphere to the Earth in midlatitudes.
- Midlatitude Storms (Eddies) transfer eastward (westerly) momentum (and heat) poleward in the upper troposphere and to the surface.
- This helps drive the Ferrel cell but also weakens slightly the Hadley cell.
- Comparing the overall overturning strength, the Ferrel cell is much weaker than the Hadley cell.

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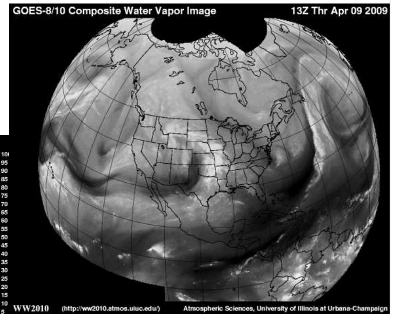
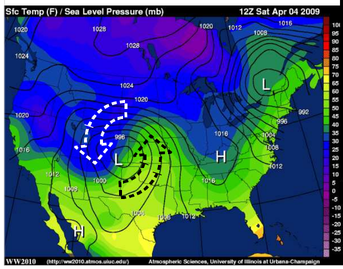
## Midlatitude Storms

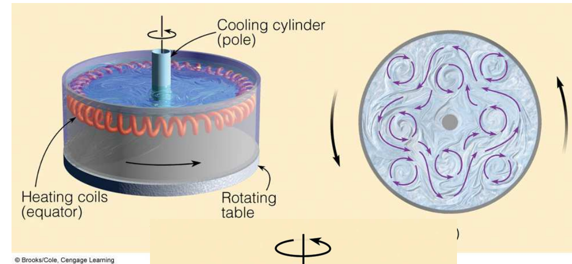
- Transport heat and momentum poleward: e.g. compare surface temperature distribution around intense low in below graphic
- Also transport moisture and with it latent heat (graphic to the right)

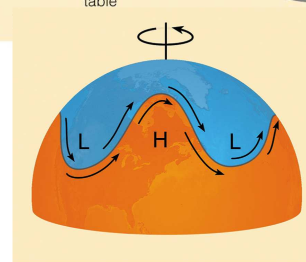


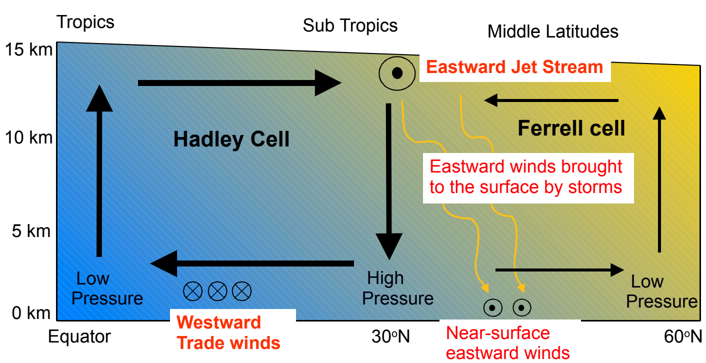



## The "Dishpan" Experiment




## The Atmosphere's Average Circulation




Surface winds are generally from the west in mid latitudes, because storm systems transport eastward winds to the surface. There can be one jet stream or two jet streams in each hemisphere, depending on the large-scale conditions.



## The Atmosphere's Average Circulation

- Ultimately driven by solar heating contrast between the equator and the poles. General Circulation acts towards compensating this differential heating, that is it transports heat poleward.
- In Hadley cell, warm air rises and moves poleward. Equator to pole Hadley cell is impossible to achieve (unstable) in the presence of rotation.
- Coriolis force deflects fluid to the right in the N.H. and to the left in the S.H. and thereby produces:
  - Trade winds, surface westerlies in midlatitudes, upper-level jet streams
- Ferrel cell is the zonal mean response to the poleward heat and momentum fluxes by eddies.