What Makes the Wind Blow?

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

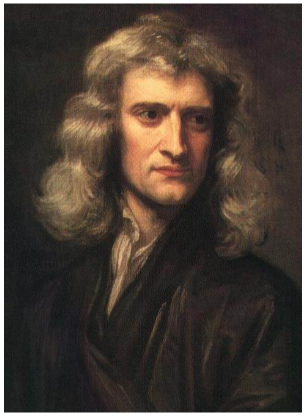
Two apparent forces due to rotation (Coriolis and centrifugal)

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

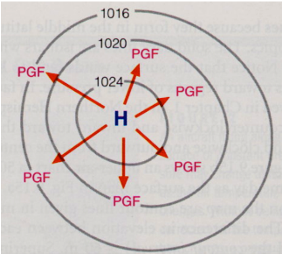


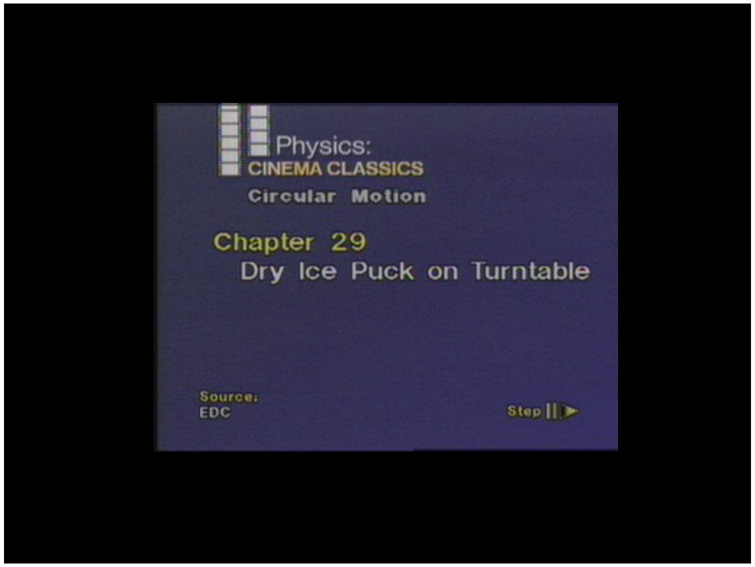
Forces Acting on the Air

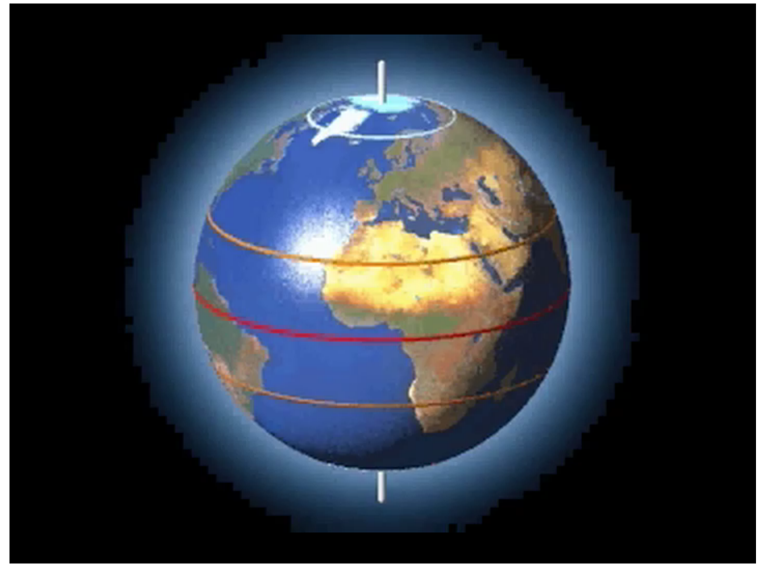
- Pressure gradient force (pushing)
- Gravity (falling)
- Friction (rubbing against the surface)
- “Apparent” forces
  - The Coriolis Force
  - Centrifugal Force

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





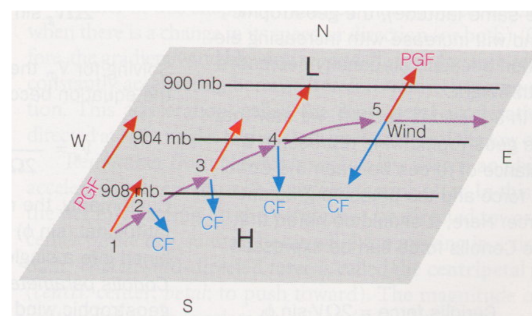


Coriolis Force

- 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



Centrifugal Force

- When viewed from a fixed reference frame, a ball swung on a string accelerates towards to center of rotation (centripetal acceleration)

- When viewed from a rotating reference frame, this inward acceleration (caused by the string pulling on the ball) is opposed by an apparent force (centrifugal force).

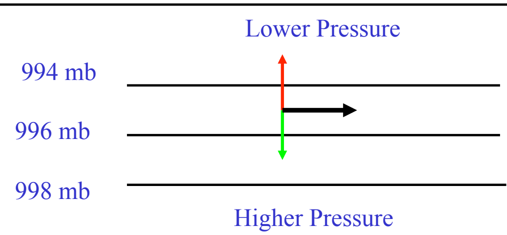
Centrifugal Force

- Magnitude
  - depends upon the radius of curvature of the curved path taken by the air parcel
  - depends upon the speed of the air parcel

- Direction
  - at right angles to the direction of movement

Geostrophic Balance

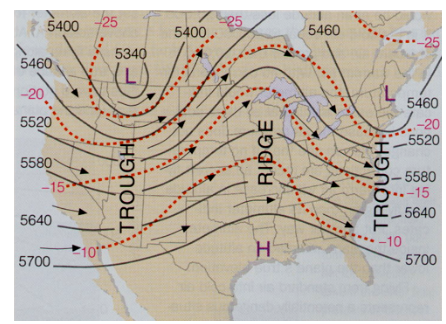
- The “Geostrophic wind” is flow in a straight line in which the pressure gradient force balances the Coriolis force.



Note: Geostrophic flow is often a good approximation high in the atmosphere (>500 meters)

Pressure patterns and winds aloft

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

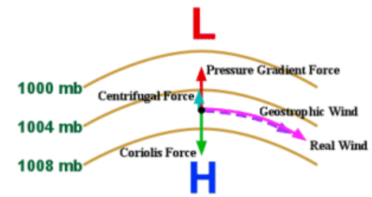


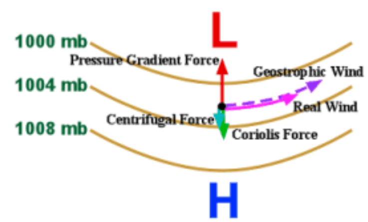
Gradient Wind Balance

- The "Gradient Wind" is flow around a curved path where there are three forces involved in the balance:
  - 1. Pressure Gradient Force
  - 2. Coriolis Force
  - 3. Centrifugal Force
- Important in regions of strong curvature (near high or low pressure centers)

Gradient Wind Balance

- Near a trough, wind slows as centrifugal force adds to Coriolis





- Near a ridge, wind speeds up as centrifugal force opposes Coriolis

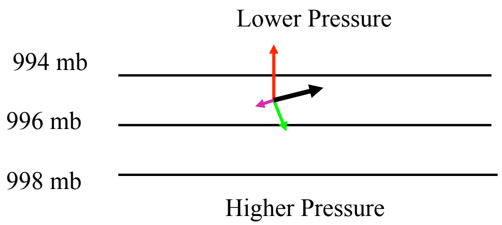
Friction is Important Near Earth's Surface

- Frictional drag of the ground slows wind down
  - Magnitude
    - Depends upon the speed of the air parcel
    - Depends upon the roughness of the terrain
    - Depends on the strength of turbulent coupling to surface
  - Direction
    - Always acts in the direction exactly opposite to the movement of the air parcel
- Important in the turbulent *friction layer* (a.k.a. the "planetary boundary layer")
  - ~lowest 1-2 km of the atmosphere
- Flow is nearly laminar aloft, friction negligible!

Three-Way Balance Near Surface (Pressure + Coriolis + Friction)

- Friction can only slow wind speed, not change wind direction
- Near the surface, the wind speed is decreased by friction, so the Coriolis force is weaker & does not quite balance the pressure gradient force
  - Force imbalance (PGF > CF) pulls wind in toward low pressure
  - Angle at which wind crosses isobars depends on turbulence and surface roughness
    - Average ~ 30 degrees

Geostrophic Wind Plus Friction

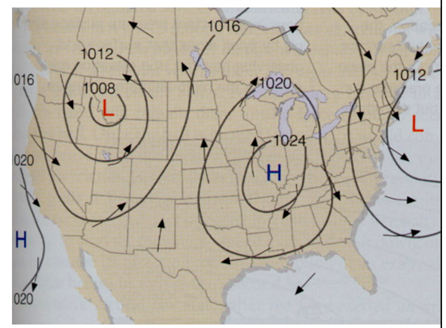


Wind doesn't blow parallel to the isobars, but is deflected toward lower pressure; this happens close to the ground where terrain and vegetation provide friction

Surface Pressure Patterns and Winds

Near the surface in the Northern Hemisphere, winds blow

- counterclockwise around and in toward the center of low pressure areas
- clockwise around and outward from the center of high pressure areas



Converging Wind, Vertical Motion, and Weather!

- Surface winds blow
  - In toward center of low pressure (convergence)
  - Out from center of high pressure (divergence)
- Air moves vertically to compensate for surface convergence or divergence
  - Surface convergence leads to divergence aloft
  - Surface divergence leads to convergence aloft

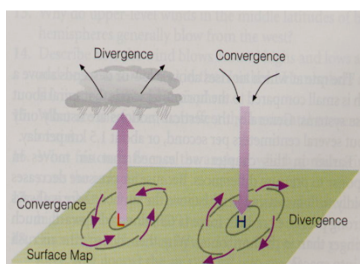
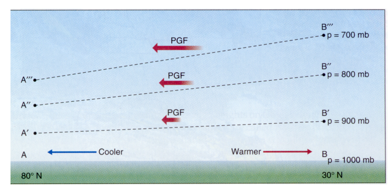
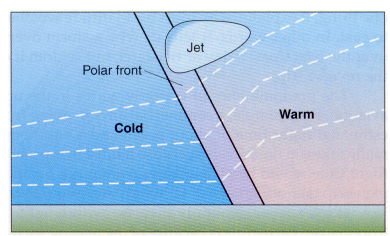


FIGURE 9.32
Winds and air motions associated with surface highs and lows in the Northern Hemisphere.

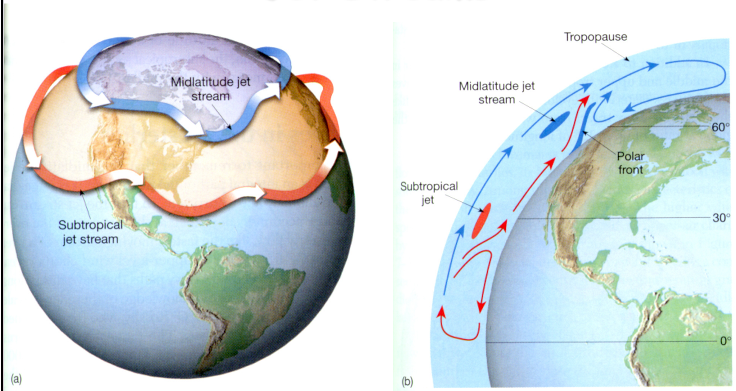
Baroclinicity and the Polar Front Jet





- 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

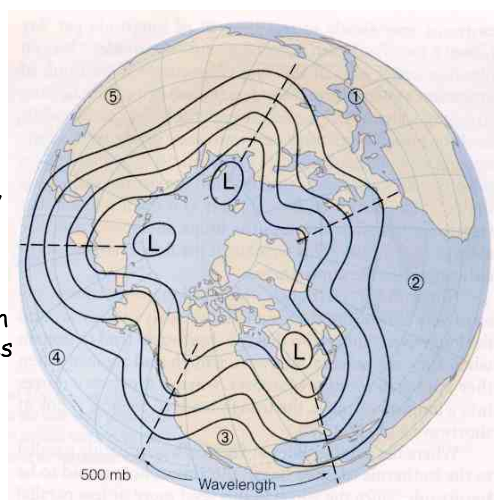
Extratropical storms are Eddies in the Jet Stream

- 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

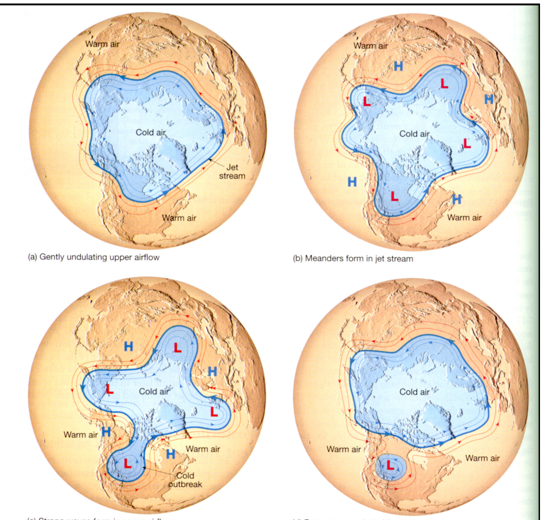
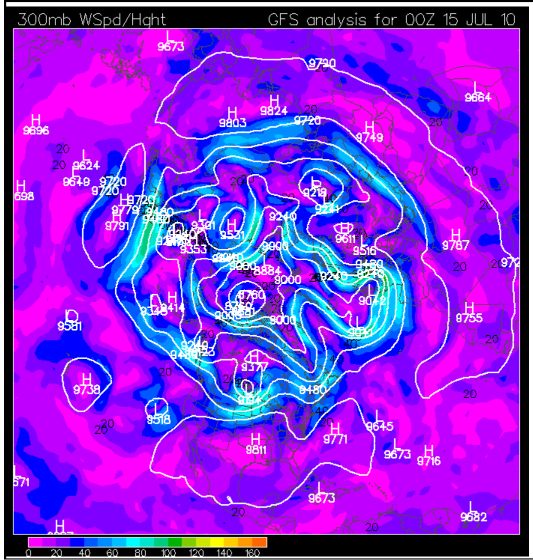


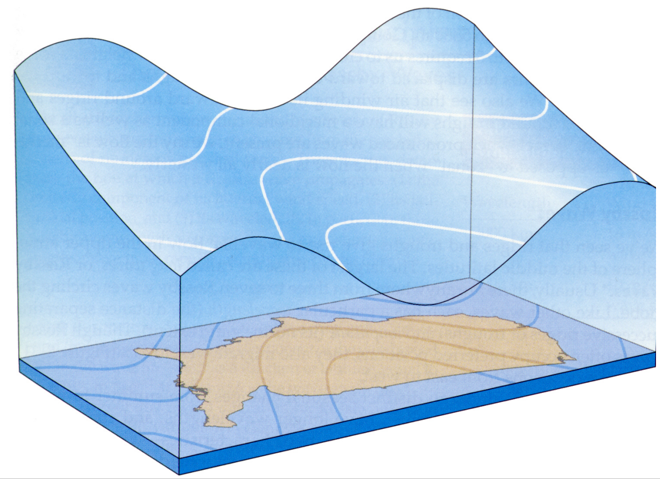
Figure 7–18 Cyclic changes that occur in the upper-level airflow of the westerlies. The flow, which has the jet stream as its axis, starts out nearly straight and then develops meanders and cyclonic activity that dominates the weather.



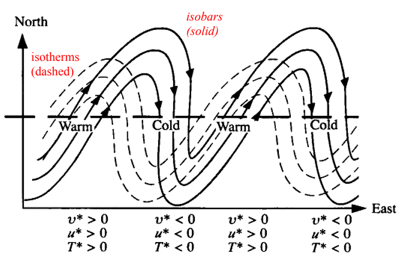
Today @ 300 mb

- "Bowl-shaped" height contours
- Jet over Canada
- Atlantic "Omega block"

Developing Transient Wave



Northward Heat Flux by Eddies



- 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

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

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

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!)