Warning!

In this unit, we switch from thinking in 1-D to 3-D on a rotating sphere

Intuition from daily life doesn't work nearly as well for this material!

What Makes the Wind Blow?

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

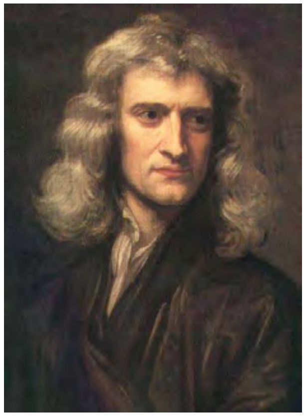
Two apparent forces due to rotation (Coriolis and centrifugal)

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

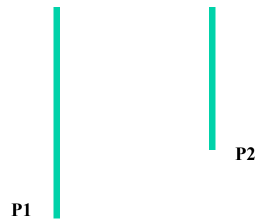


Forces Acting on the Air

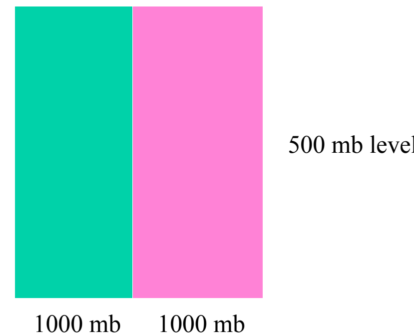
- Pressure gradient force (pushing)
- Gravity (falling)
- Friction (rubbing against the surface)
- "Apparent" forces
  - The Coriolis Force
  - Centrifugal Force

Why does pressure vary horizontally?

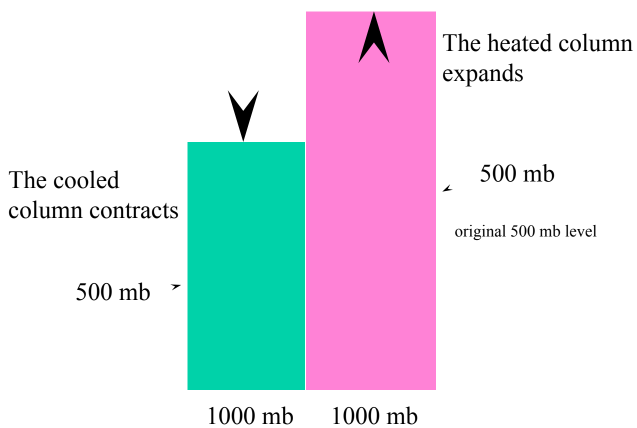
- Elevation changes cause pressure differences
- These are balanced by gravity and don't cause wind to blow
- *But why does pressure vary between locations which are at the same elevation?*



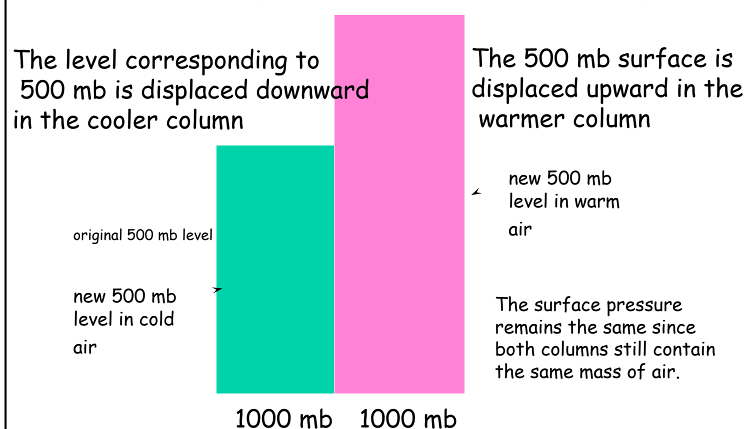
Thought Experiment:
Consider two columns of air with the same temperature and distribution of mass



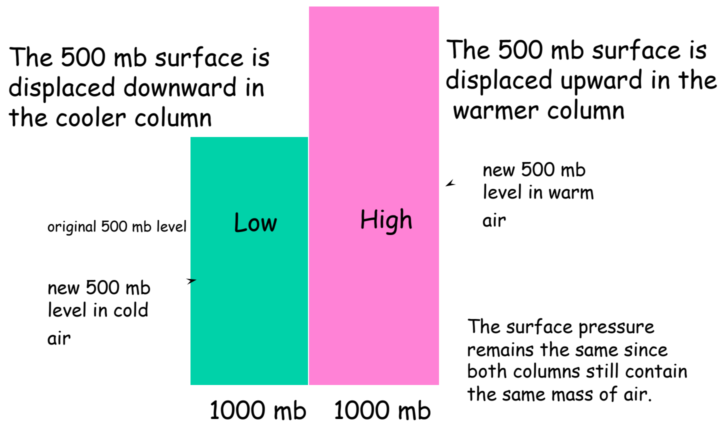
Now cool the left column and heat the right



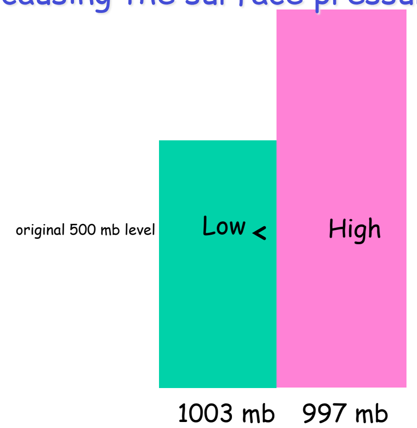
The level of the 500 mb surface changes; the surface pressure remains unchanged



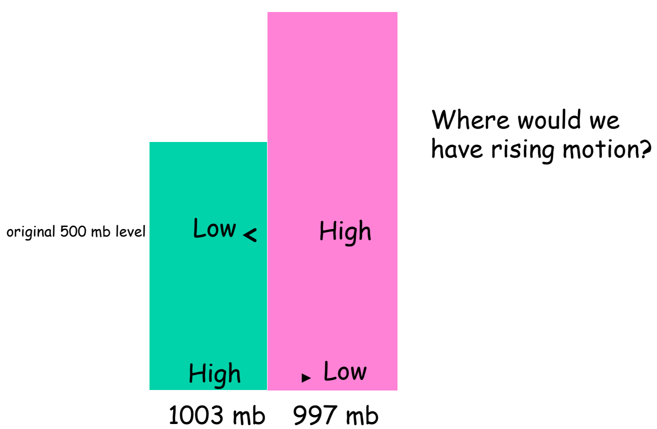
A pressure difference in the horizontal direction develops above the surface



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…



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

Surface Pressure Variations

Differential heating produces spatial patterns of atmospheric mass!

Altitude-adjusted surface station pressures are used to construct sea level pressure contours

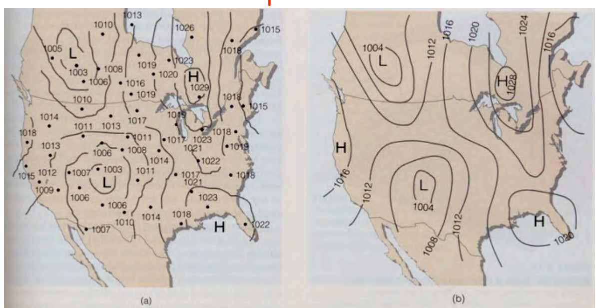
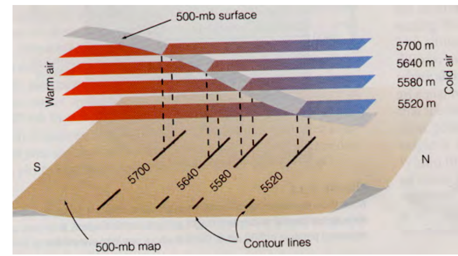


FIGURE 9.9
(a) Sea-level isobars drawn so that each observation is taken into account. Not all observations are plotted. (b) Sea-level isobars after smoothing

Constant pressure charts (pressure as a vertical coordinate)

- Constant pressure (isobaric) charts are often used by meteorologists
- Isobaric charts plot variation in height on a constant pressure surface (e.g., 500 mb) … exactly analogous to topographic maps
- In this example a gradient between warm and cold air produces a sloping 500 mb pressure surface
  - Pressure decreases faster with height in a colder (denser) air mass
- Where the slope of the pressure surface is steepest the height contours are closest together



Troughs and Ridges

- Temperature gradients generally produce pressure gradients (equivalently, height gradients of isobars)
- Isobars usually decrease in height toward the pole (cooler underlying temperatures)
- Contour lines are usually not straight:
  - **Ridges** (elongated highs) occur where air is warm
  - **Troughs** (elongated lows) occur where air is cold

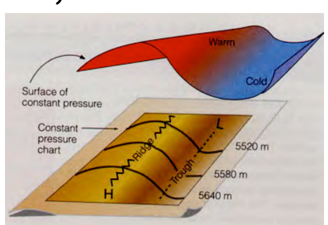
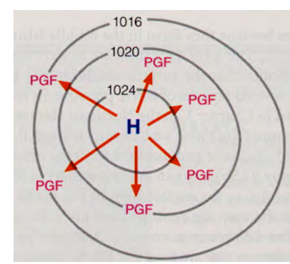
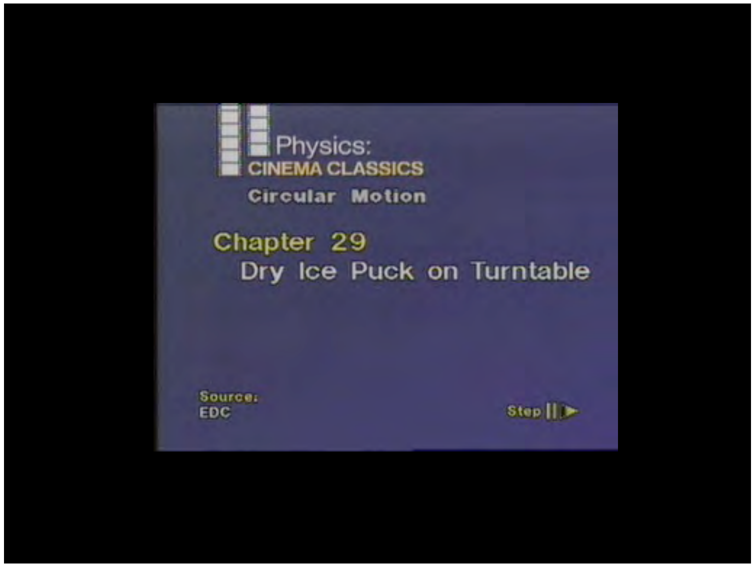


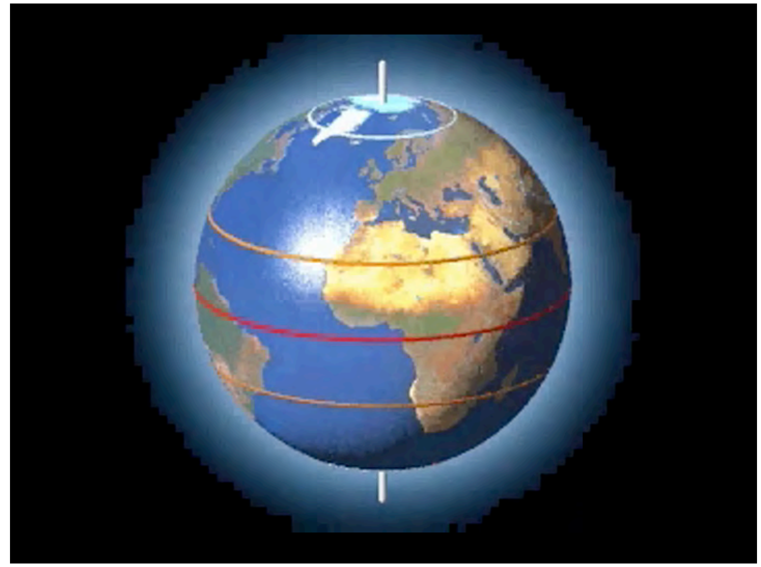
FIGURE 9.14
The wavelike patterns of a constant pressure surface reflect the changes in air temperature. An elongated region of warm air aloft shows up on a constant pressure chart (isobaric map) as higher heights and a ridge; the colder air shows as lower heights and a trough.

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





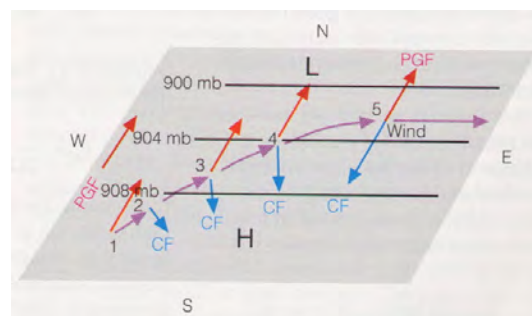


Coriolis Force

- 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



Geostrophic Balance

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

Lower Pressure

994 mb

996 mb

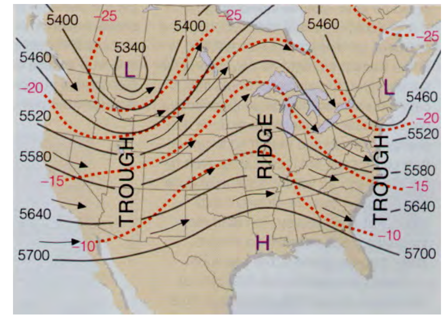
998 mb

Higher Pressure

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



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

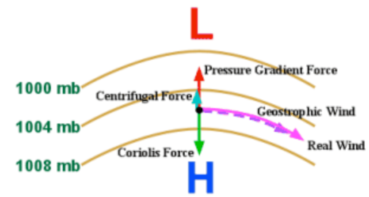
- Magnitude
  - depends upon the radius of curvature of the curved path taken by the air parcel
  - depends upon the speed of the air parcel
- Direction
  - at right angles to the direction of movement

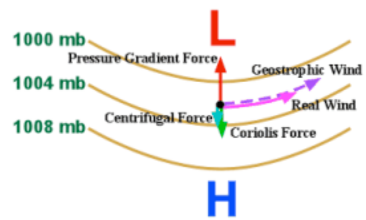
Gradient Wind Balance

- 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 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

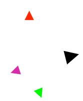
Geostrophic Wind Plus Friction

Lower Pressure

994 mb

996 mb

998 mb



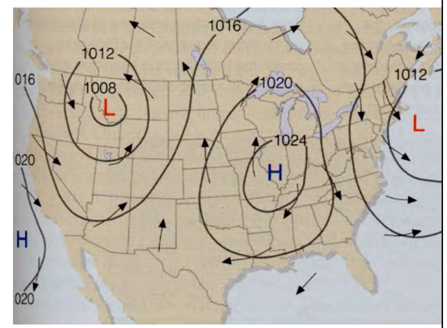
Higher Pressure

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

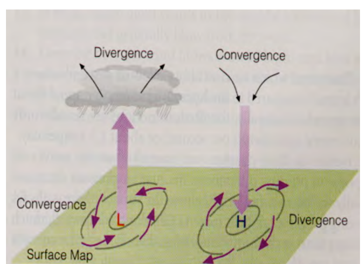


FIGURE 9.32
Winds and air motions associated with surface highs and lows in the Northern Hemisphere.

Remember

- 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