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

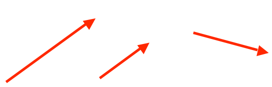
$$\sum \vec{F} = m\vec{a}$$

- 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

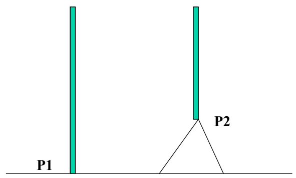
- Pressure gradient force (pushing)
- Gravity (falling)
- Friction (rubbing against the surface)

- "Apparent" forces
  - The Coriolis Force
  - Centrifugal Force



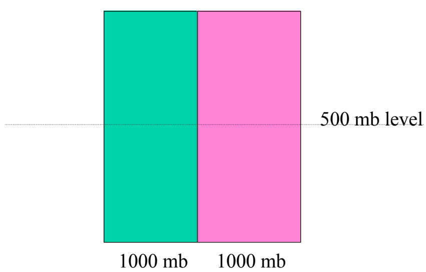
Why does pressure vary horizontally?

- 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?*

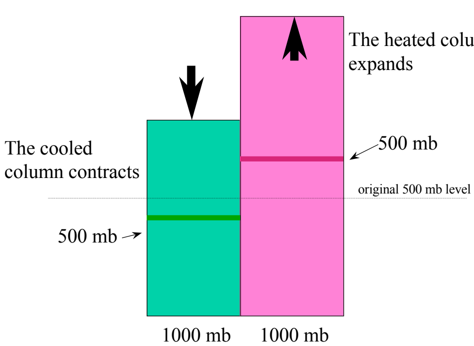


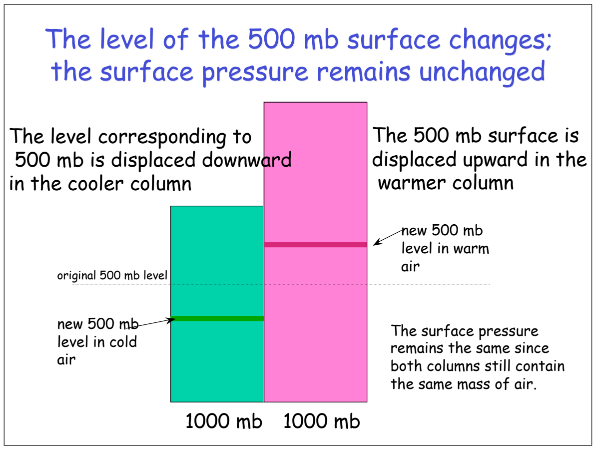
Thought Experiment:

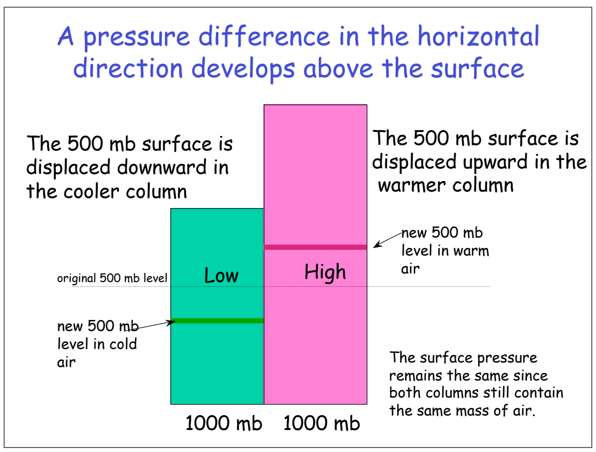
Consider two columns of air with the same temperature and distribution of mass

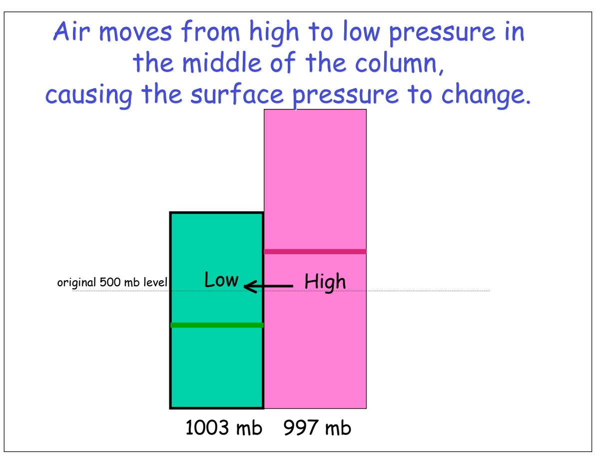


Now cool the left column and heat the right

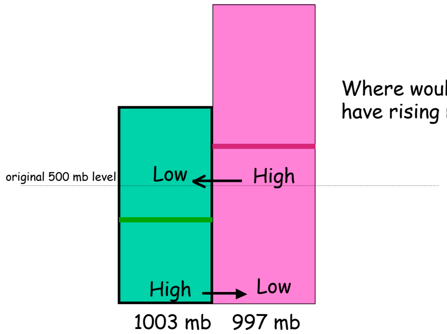



The level of the 500 mb surface changes; the surface pressure remains unchanged
The level corresponding to 500 mb is displaced downward in the cooler column
The 500 mb surface is displaced upward in the warmer column
new 500 mb level in warm air
original 500 mb level
new 500 mb level in cold air
The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


A pressure difference in the horizontal direction develops above the surface
The 500 mb surface is displaced downward in the cooler column
The 500 mb surface is displaced upward in the warmer column
new 500 mb level in warm air
original 500 mb level
Low
High
new 500 mb level in cold air
The surface pressure remains the same since both columns still contain the same mass of air.
1000 mb
1000 mb


Air moves from high to low pressure in the middle of the column, causing the surface pressure to change.
original 500 mb level
Low
High
1003 mb
997 mb

Air moves from high to low pressure at the surface…



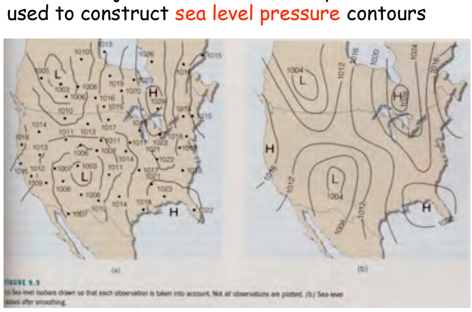
Where would we have rising motion?

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 along a horizontal surface.
- The pressure differences then induced flow in the fluid
- This is a microcosm of how the atmosphere converts heating into motions

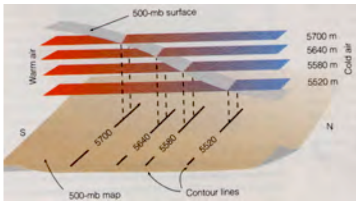
Surface Pressure Maps

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



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)
- 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
- Isobars usually decrease in height from south to north (cooler temperatures)
- But contour lines are usually not straight.
  - **Ridges** (elongated highs) occur where air is warm
  - **Troughs** (elongated lows occur where air is cold

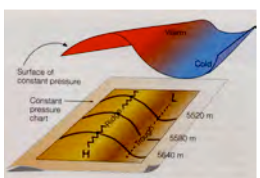
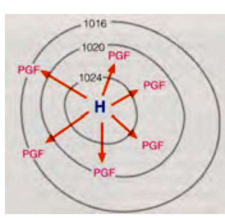


FIGURE 9.14
The wavelike patterns of a constant pressure surface reflect the changes in ai temperature. An elongated region of warm air aloft shows up on a constant pressure chart (isobaric map) as higher heights and a ridge; the colder air shows as lower heights and a trough.

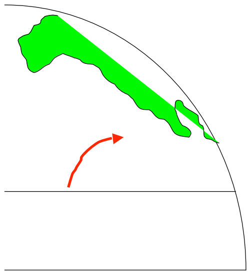
Pressure Gradient Force

- 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

Apparent force due to rotation of the earth



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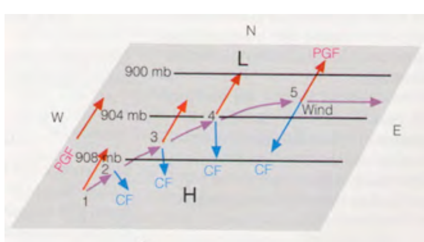
Coriolis Force

- 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

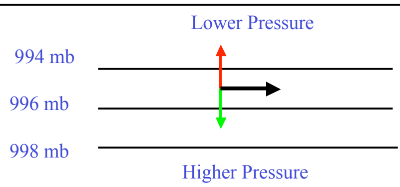
Coriolis Force

- Acts to right in northern hemisphere
- Proportional to wind speed



Geostrophic Balance

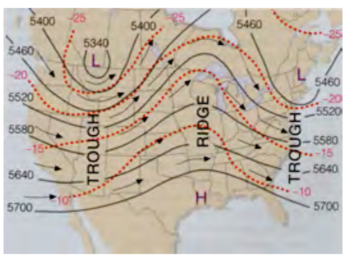
- The "Geostrophic wind" is flow in a straight line in which the pressure gradient force balances the Coriolis force.



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

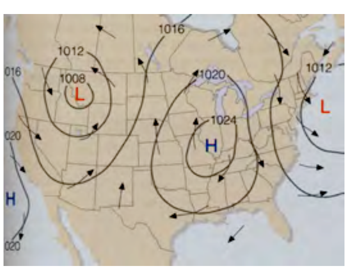
Pressure patterns and winds aloft

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



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



Why doesn't the wind blow from high to low pressure?

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

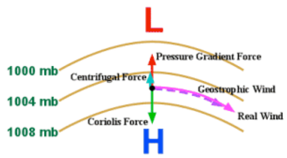
- Magnitude
  - depends upon the radius of curvature of the curved path taken by the air parcel
  - depends upon the speed of the air parcel
- Direction
  - at right angles to the direction of movement

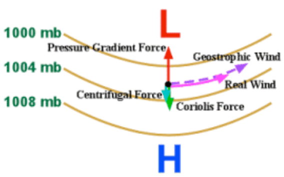
Gradient Wind Balance

- 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 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

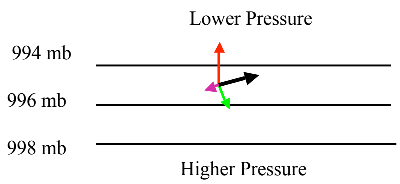
Friction is important near Earth's surface

- 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*** (planetary boundary layer)
    - ~lowest 1-2 km of the atmosphere
- Flow is nearly laminar aloft, friction negligible!

Three-Way Balance pressure + coriolis + friction

- Friction can only slow wind speed, not change wind direction
- Therefore, in the northern hemisphere, if the wind speed is decreased by friction, the Coriolis force will be decreased and will not quite balance the pressure gradient force
  - Force imbalance (PGF > CF) pushes wind in toward low pressure
  - Angle at which wind crosses isobars depends on turbulence and surface roughness
    - Average ~ 30 degrees

Geostrophic wind plus friction



The wind no longer blows parallel to the isobars, but is deflected toward lower pressure; this happens close to the ground where terrain and vegetation provide friction

Winds and vertical air motion

- 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

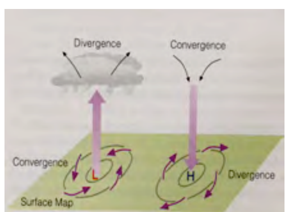
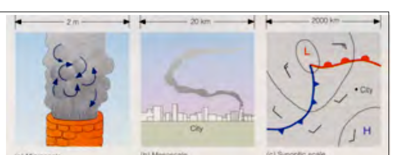


FIGURE 9.32
Winds and air motions associated with surface highs and lows in the Northern Hemisphere.

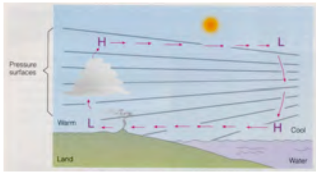
Scales of Motion



- Microscale: meters
  - Turbulent eddies
    - Formed by mechanical disturbance or convection
    - Lifetimes of minutes
- Mesoscale: km's to 100's of km's
  - Local winds and circulations
    - Land/sea breezes, mountain/valley winds, thunderstorms, tornadoes
    - Lifetimes of minutes to hours
- Synoptic scale: 100's to 1000's of km's
  - Circulations around high and low pressure systems
    - Lifetimes of days to weeks
- Global scale: systems ranging over entire globe
  - Seasonal, interannual, climatological

Sea and Land Breezes

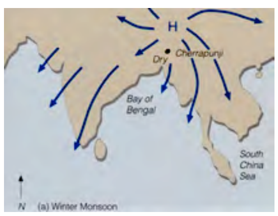
- Sea and land breezes are
  - Mesoscale coastal winds
  - Thermal circulations driven by differential heating/cooling of adjacent land and water surfaces
  - Most prevalent when/where solar heating is strong
- Sea breeze development
  - Solar heating raises land temperature more than water
  - Air in contact with land warms and rises
  - Cooler (denser) sea air moves in to replace rising air over land
  - Air sinks over the water in response to surface air movement, producing return circulation (land-to-sea breeze) aloft



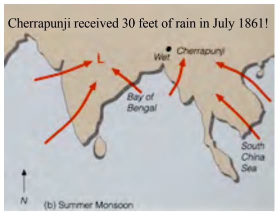
- Sea breezes
  - Cool coastal communities
  - Bring more humid air
    - Haze
    - Fog
  - Often produce summer thunderstorms inland from the coast

The *Monsoon*

- Monsoon winds are
  - Seasonal
  - Common in eastern and southern Asia and Africa
  - Similar to huge land/sea breeze systems
- During winter strong cooling produces a shallow high pressure area over Siberia
  - Subsidence, clockwise circulation and flow out from the high provide fair weather for southern and eastern Asia
- During summer, air over the continent heats and rises, drawing moist air in from the oceans
  - Convergence and topography produce lifting and heavy rain formation

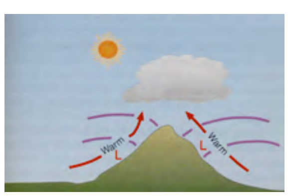


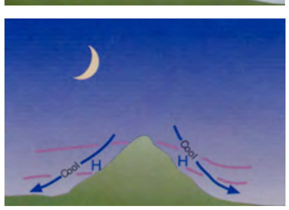
Cherrapunji received 30 feet of rain in July 1861!



Mountain/Valley winds

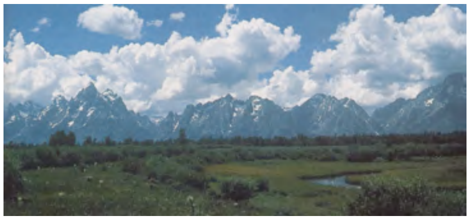
- Sunlight heats mountain slopes during the day and they cool by radiation at night
- Air in contact with surface is heated/cooled in response
- A difference in air density is produced between air next to the mountainside and air at the same altitude away from the mountain
- Density difference produces upslope (day) or downslope (night) flow
- Daily upslope/downslope wind cycle is strongest in clear summer weather when prevailing winds are light





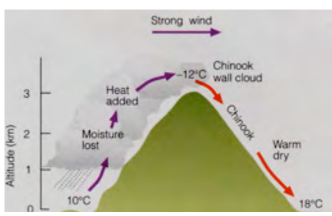
Mountain/Valley winds (cont'd)

- Upslope flow during the day leads to formation of clouds and precipitation along mountain ranges
  - When is the best time for hiking and climbing?
- Upslope flow along the Front Range transports pollutants from the urban corridor into the mid-troposphere
- Why do I always seem to bike into the wind?



Chinook Downslope Winds

- Main source of warming is compression during downslope flow
  - Key is loss of moisture on upwind slope so downslope heating occurs at higher dry adiabatic rate
- Latent heat release from condensation during upwind ascent also contributes
  - If condensed water is removed as precipitation on upwind slope



Would we experience a Chinook wind if the upwind atmosphere was unstable?

Remember

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- Two apparent forces due to rotation (Coriolis and centrifugal)
- Large-scale flow is dominated by gravity/pressure and Coriolis … friction and centrifugal important locally