Air Pressure and Winds

Chapter 8
Pressure

- Recall that
  - Pressure is force per unit area
  - Air pressure is determined by the weight of air above
- A change in pressure over some distance (pressure gradient) causes air to move
- What is the difference between surface pressure and sea level pressure?
Remember: hydrostatic balance

What keeps air from always moving downwards due to gravity?

*A balance between gravity and the pressure gradient force.*

\[
\frac{\Delta P}{\Delta z} = \rho g
\]

So:

\[
\Delta P = \rho g \Delta z
\]

Note the vertical scale on the figure of density with altitude. For the lowest 10 km of the atmosphere, the density and pressure change rapidly with height. Why is this? The density changes rapidly with height since the atmosphere is compressible. The weight of the column above (due to gravity) squeezes the air molecules close together, increasing the density. Since the product of density and gravity is balanced by the vertical pressure gradient, that is, how \( p \) changes with height, the pressure gradient and pressure must be large too.
How to measure pressure?

A recording barograph. A partially evacuated cylinder (aneroid cell) changes its volume as the air pressure changes. A rotating drum and pen trace the atmospheric pressure.

A simple, but effective mercury in glass barometer. Change in pressure displaces the column upward or downward. Mercury is used as it is very stable.
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- 1085 mb (32.03 in.) Highest recorded sea-level pressure: Tongsontsen, Mongolia (December 2001)
- 1064 mb (31.42 in.) Highest recorded sea-level pressure in the continental United States (excluding Alaska): Miles City, Montana (December 1983)
- 1013.25 mb (29.92 in.) Standard sea-level pressure
- 920 mb (27.17 in.) Hurricane Katrina during landfall (August 2005)
- 882 mb (26.04 in.) Hurricane Wilma (October 2005)
- 870 mb (25.70 in.) Lowest recorded sea-level pressure: Typhoon Tip (October 1979)

Range of surface pressures. A large range!!

Ahrens and Henson
Why does pressure vary horizontally?

Two columns - same temperature
same distribution of mass

1000 mb

500 mb level

1000 mb 1000 mb
Cool the left column; warm the right column

The heated column expands

The cooled column contracts

500 mb

original 500 mb level

1000 mb 1000 mb

500 mb
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.

The surface pressure remains the same since both columns still contain the same mass of air.
A pressure difference in the horizontal direction develops above the surface.

The 500 mb surface is displaced downward in the cooler column and upward in the warmer column.

The surface pressure remains the same since both columns still contain the same mass of air.
Air moves from high to low pressure in middle of column, causing surface pressure to change.
Air moves from high to low pressure at the surface…

In which column would you expect rising motion to be taking place?
What have we just observed?

- Starting with a uniform atmosphere at rest, we introduce differential heating
- The differential heating causes different rates of expansion in the air
- The differing rates of expansion result in pressure differences along a horizontal surface aloft.
- The pressure differences induce horizontal flow aloft and at the surface
- This is a microcosm of how the atmosphere converts heating into motions
The correction is as follows: \( p_{\text{cor}} = p_{\text{obs}} + \rho g \Delta z \) where \( \Delta z \) is the height change between sea level and the station altitude. Note that a station can be below sea level.
SLP maps characterized by areas of higher and lower pressure
Constant pressure charts

- 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 value 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
Pressure patterns and winds aloft

- At upper levels, winds blow parallel to the pressure/height contours.
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? To answer this, we need to examine the forces that govern winds in the atmosphere.
Forces and winds

• Pressure gradients produce air movement
• Multiple forces act simultaneously to cause the wind direction to differ from the direction of decreasing pressure
• Newton’s laws of motion describe the relationship between forces and motion
  – 1\textsuperscript{st} Law: an object at rest will stay at rest and an object in motion will remain in motion (and travel at a constant velocity along a straight line) as long as no net force is exerted on the object
  – 2\textsuperscript{nd} 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 (more over rough terrain compared to over oceans)
Forces expressed as vectors

• Forces have two properties
  – Magnitude or Size
  – Direction

• Vectors have two properties
  – Length of arrow denotes magnitude
  – Direction of arrow denotes direction
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

Illustrate with the classic merry go round example

This apparent force is only sensed in the frame of reference that is rotating. Since Earth rotates, on Earth we experience this same apparent force.
Coriolis Force

• Apparent force due to rotation of the earth

• 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
• Stronger for faster wind
Geostrophic Wind

- The Geostrophic wind is flow in which the pressure gradient force balances the Coriolis force.

Note: Geostrophic flow is often a good approximation above the Earth’s surface (>500 meters)
Centrifugal Force

- When viewed from a fixed reference frame, a ball swung on a string accelerates towards the 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; strong curvature implies a larger force
  – 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. Centripetal Force

• Important near high or low pressure centers
Gradient Wind

For cyclonic flow, the centrifugal force points outward, as does the CF force. PGF needs to balance both so CF needs to decrease which implies the wind speed must decrease. This allows the wind to follow a circular path around low pressure in the N. Hemisphere.

For anticyclonic flow, the outward centrifugal force is aligned with the PGF. So CF needs to increase to balance which means that the wind speed must increase. If the wind speed did not increase, the flow would not be circular but would blow outwards from high pressure.

We conclude that for a given pressure gradient, winds are stronger around high pressure compared to low pressure.

But reality tells us something different?
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 upon how uniform the wind field is
  – Direction
    • Always acts in the direction opposite to the movement of the air parcel
  – Important in the *friction layer* (planetary boundary layer)
    • ~lowest 1000 m of the atmosphere
What happens when we add 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 surface roughness
    • Average ~ 30 degrees
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
  – So we have rising motion above surface lows (clouds and weather) and sinking motion over surface highs leading to cloud free skies and fair weather
Upper Level Maps Show the Height of Constant Pressure Surfaces

- The height of the pressure surface can be contoured on a map, where contour lines represent the height of the pressure surface, in this case 500 mb.
- Warm air aloft expands the atmosphere, making the 500 mb pressure surface higher.
- Cold air aloft makes the 500 mb pressure surface lower.
Upper Level Maps Show the Height of Constant Pressure Surfaces

- Regions of low height on an isobaric map are typically called **troughs**.
- Regions of high height are called **ridges**.
- The troughs correspond to low pressure on a constant height surface, and the ridges correspond to high pressure.
Upper Level Maps Show the Height of Constant Pressure Surfaces

- For example, at the right is a 500 mb isobaric map.
- Plotted are contours showing the height of the 500 mb pressure surface.
- Low heights are equivalent to low pressure.
- When deriving the equations of motion for the atmosphere, using coordinates of pressure rather than height is very logical.
Upper Level Map

- Winds blow almost exactly parallel to constant height surfaces.
- Low heights (pressure) are on the left in the **Northern Hemisphere** (counterclockwise motion), and high heights (pressure) are on the right (clockwise motion).
- Low heights (pressure) are on the right in the **Southern Hemisphere** (clockwise motion), and high heights (pressure) are on the left (counterclockwise motion).
- Low height areas are called troughs, and high height areas are called ridges.
Upper Level Map

- This map also shows temperatures at the 500 hPa surface.
- It can be seen that cold temperatures in the middle to upper troposphere are associated with low heights of the 500 hPa surface.
- Warm temperatures in the middle to upper troposphere are associated with high 500 hPa heights.
Upper Level Map

- This map shows heights, wind vectors, and contours of wind speed at the 300 hPa surface.
- Wind speed is greatest where the height contours are packed closer together.
- **Jet stream** shows up as a narrow band of strong winds, located to the north of Colorado.
- Bulk of cold air is located to the north of the strong jet stream.
- In this plot, there are actually two jet streams in the east Pacific.