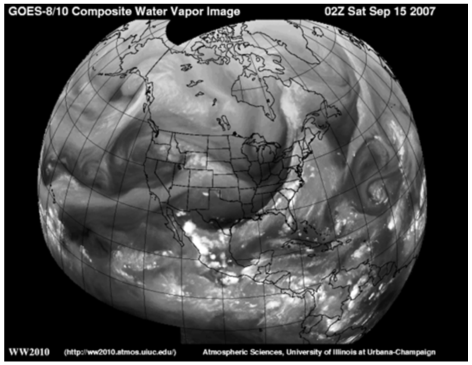
Chapter 7: Forces and Force Balances



- Forces that Affect Atmospheric Motion
- Force Balance
- Geostrophic Balance and Jetstream

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Forces that Affect Atmospheric Motion

- Fundamental force -
  - Pressure gradient force
  - Gravitational force
  - Frictional force
- Apparent force -
  - Centrifugal force
  - Coriolis force

- Newton's second law of motion states that the rate of change of momentum (i.e., the acceleration) of an object, as measured relative to coordinates fixed in space, equals the sum of all the forces acting.
- For atmospheric motions of meteorological interest, the forces that are of primary concern are the pressure gradient force, the gravitational force, and friction. These are the *fundamental* forces.
- For a coordinate system rotating with the earth, Newton's second law may still be applied provided that certain *apparent* forces, the centrifugal force and the Coriolis force, are included among the forces acting.

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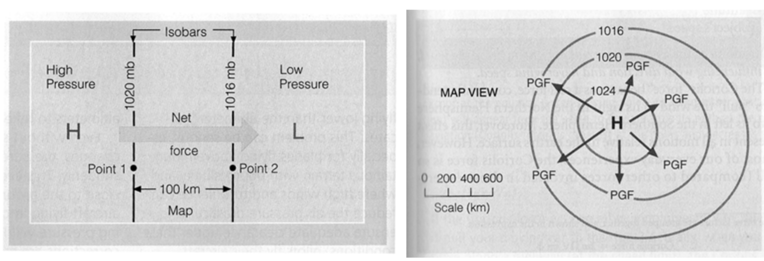
Pressure Gradient Force



(from Meteorology Today)

- PG = (pressure difference) / distance
- Pressure gradient force goes from high pressure to low pressure.
- Closely spaced isobars on a weather map indicate steep pressure gradient.

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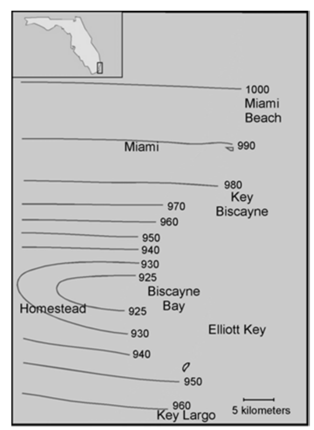
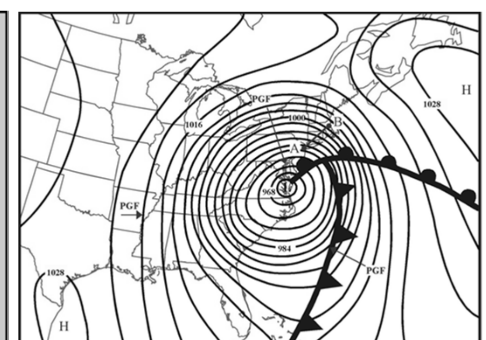
Examples of Pressure Gradient

Hurricane Andrew, 1992



Courtesy of American Meteorological Society

Extratropical Cyclone



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Pressure Gradients

- Pressure Gradients
  - The pressure gradient force initiates movement of atmospheric mass, wind, from areas of higher to areas of lower pressure
- Horizontal Pressure Gradients
  - Typically only small gradients exist across large spatial scales (1mb/100km)
  - Smaller scale weather features, such as hurricanes and tornadoes, display larger pressure gradients across small areas (1mb/6km)
- Vertical Pressure Gradients
  - ***Average vertical pressure gradients are usually greater than extreme examples of horizontal pressure gradients*** as pressure always decreases with altitude (1mb/10m)

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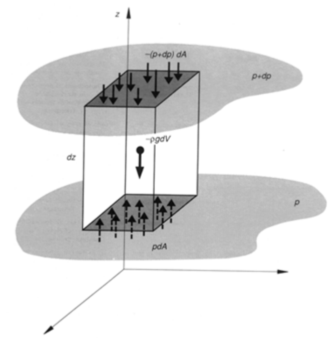
Balance of Force in the Vertical: Hydrostatic Balance



(from *Climate System Modeling*)

Vertical pressure force = Gravitational force

$- (dP) \times (dA) = \rho \times (dz) \times (dA) \times g$

$$dP = -\rho g dz$$

Since $P = \rho RT$,

$dP = -P/RT \times gdz$

$dP/P = -g/RT \times dz$

$P = P_s \exp(-gz/RT)$

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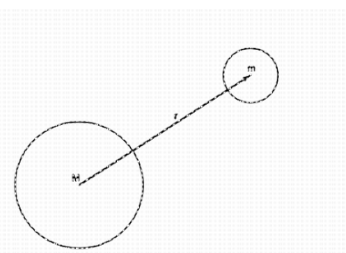
Gravitational Force

- Newton's law of universal gravitation states that any two elements of mass in the universe attract each other with a force proportional to their masses and inversely proportional to the square of the distance separating them.
- Thus, if the earth is designated as mass M and m is a mass element of the atmosphere, then the force per unit mass exerted on the atmosphere by the gravitational attraction of the earth is



Two spherical masses whose centers are separated by a distance r.

$$\frac{\mathbf{F}_g}{m} \equiv \mathbf{g}^* = -\frac{GM}{r^2}\left(\frac{\mathbf{r}}{r}\right)$$

$r = a + z$ (a: earth radius; z: height above surface)

$$\mathbf{g}^* = \frac{\mathbf{g}_0^*}{(1 + z/a)^2}$$

where $\mathbf{g}_0^* = -(GM/a^2)(\mathbf{r}/r)$ is the gravitational force at mean sea level.

For meteorological applications,

$z \ll a$ ➔ $\boxed{\mathbf{g}^* = \mathbf{g}_0^*}$

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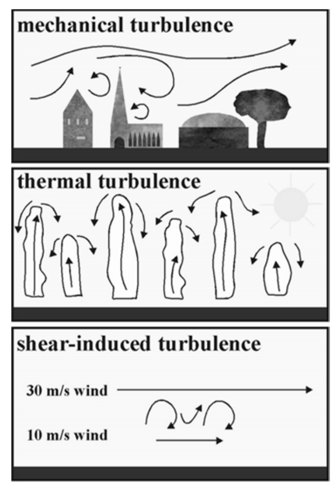
Frictional Force



- Frictional force (drag) is strongest near the Earth's surface and decreases rapidly with height.
- The atmospheric layer in which frictional force is important is call thed boundary layer, whose depth can vary from a few hundred meters to a few thousand meters.
- There are three sources to generate turbulence eddies to give rise to the frictional force: (1) mechanical turbulence (airs encounter surface roughness), (2) thermal turbulence (air near Earth's surface get heated, and (3) wind-shear induced turbulence.

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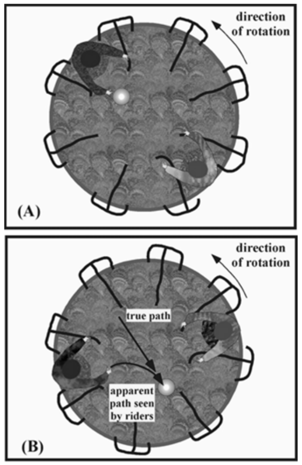
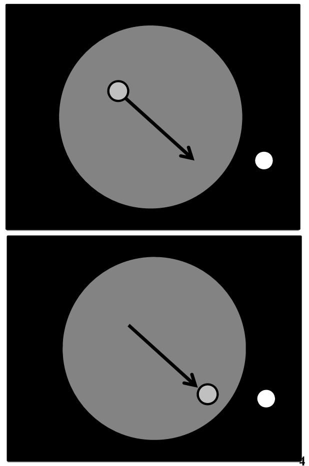
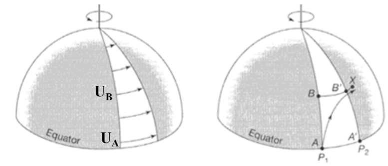
Example on a Merry-Go-Around





Coriolis Force – Conservation of Angular Momentum



(from *The Earth System*)

Absolute angular momentum at **A** = Absolute angular momentum at **B**

U_A * (radius at A) = U_B * (radius at B)

U_A * (Earth's Radius * Cos(latitude at A) = U_B * (Earth's Radius * Cos(latitude at B)

$U_A = U_B$ * [cos(latitude at B) / cos(latitude at A)]

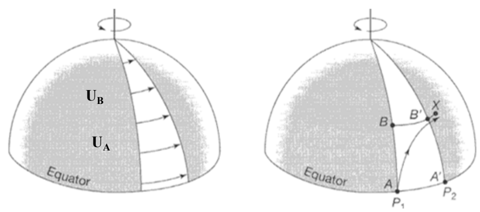
$\mathbf{U_A > U_B}$

➔ A northward motion starting at A will arrive to the east of B due to the conservation of angular momentum

➔**An apparent force (Coriolis Force) = *f V*, where *f* = 2*Ω*Sin(lat)**
where Ω=7.292x10^{-5} rad s^{-1}

➔ **To the right (left) of the motion in Northern (Southern) Hemisphere**

Coriolis Force



(from *The Earth System*)

❑ First, Point A rotates faster than Point B ($U_A > U_B$)

➔ $U_A > U_B$

➔ A northward motion starting at A will arrive to the east of B

➔ It looks like there is a "force" pushing the northward motion toward right

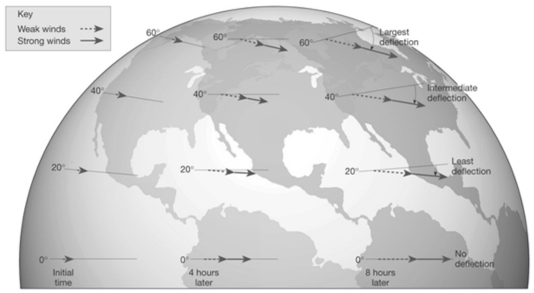
➔ This apparent force is called "Coriolis force":

Coriolis Force = *f V*
where *f* = 2*Ω*Sin(lat) and Ω=7.292x10^{-5} rad s^{-1}

Coriolis Force

- Coriolis force causes the wind to deflect to the right of its intent path in the Northern Hemisphere and to the left in the Southern Hemisphere.
- The magnitude of Coriolis force depends on (1) the rotation of the Earth, (2) the speed of the moving object, and (3) its latitudinal location.
- The stronger the speed (such as wind speed), the stronger the Coriolis force.
- The higher the latitude, the stronger the Coriolis force.
- The Corioils force is zero at the equator.
- Coriolis force is one major factor that determine weather pattern.

Coriolis Force Change with latitudes



(from *The Atmosphere*)

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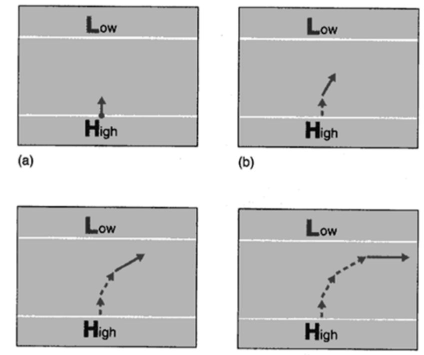
How Does Coriolis Force Affect Wind Motion?



(from *Weather & Climate*)

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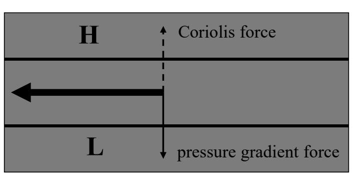
Geostrophic Balance



- By doing scale analysis, it has been shown that large-scale and synoptic-scale weather system are in geostropic balance.
- Geostrophic winds always follow the constant pressure lines (isobar). Therefore, we can figure out flow motion by looking at the pressure distribution.

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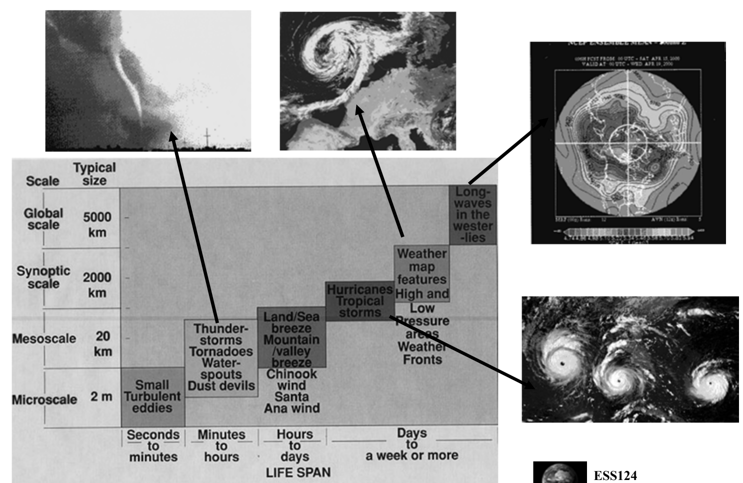
Scales of Motions in the Atmosphere



(from Meteorology Today by C. Donald Ahrens © 1994 West Publishing Company)

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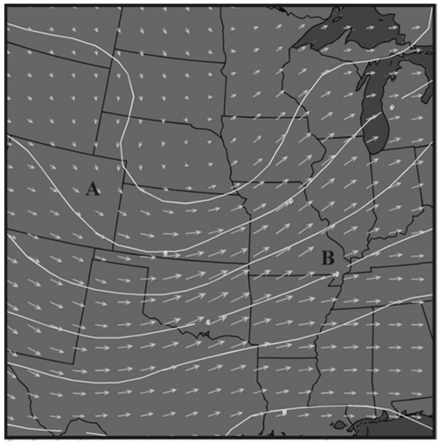
Example: Winds and Height on 500mb



Courtesy of the Department of Atmospheric Sciences
University of Illinois at Urbana-Champaign

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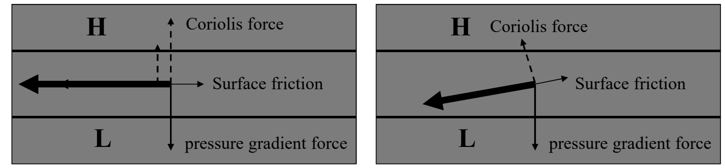
Frictional Effect on Surface Flow



- Surface friction force slows down the geostrophic flow.
- The flow turns into (out of) the low (high) press sides.
- Convergence (divergence) is produced with the flow.

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Surface Friction

- Friction Force = c * V
  c = friction coefficient
  V = wind speed

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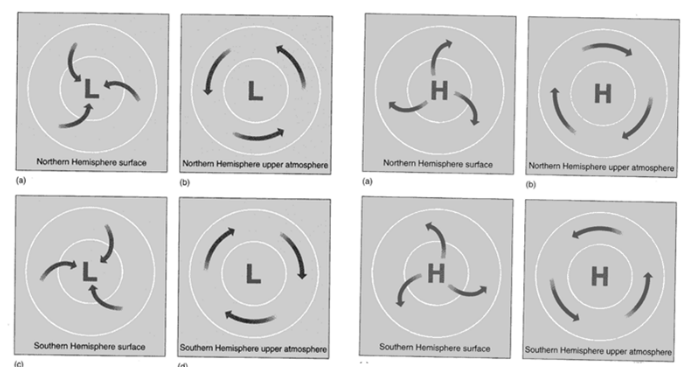
Surface Geostrophic Flow

Cyclonic Flow **Anticyclonic Flow**



(figures from *Weather & Climate*)

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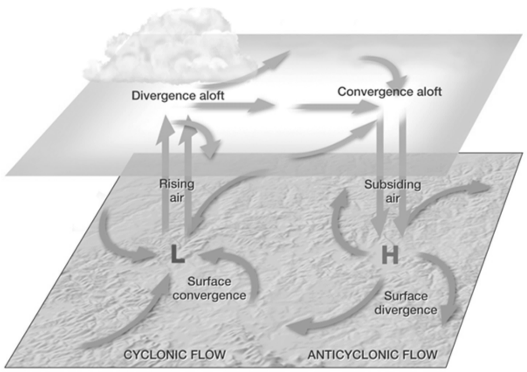

(from *The Atmosphere*)

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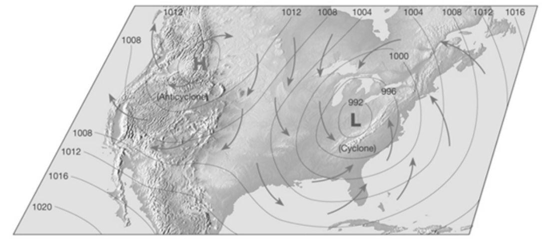
Surface High and Low Pressure Systems



(from *The Atmosphere*)

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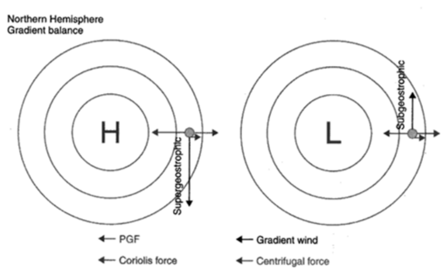
Super- and Sub-Geostrophic Wind



(from *Meteorology: Understanding the Atmosphere)*

❑ For high pressure system

➔gradient wind > geostrophic wind

➔supergeostropic.

❑ For low pressure system

➔gradient wind < geostrophic wind

➔subgeostropic.

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Gradient Wind Balance

- The three-way balance of horizontal pressure gradient, Coriolis force, and the centrifugal force is call the ***gradient wind balance***.
- The gradient wind is an excellent approximation to the actual wind observed *above* the Earth's surface, especially at the middle latitudes.

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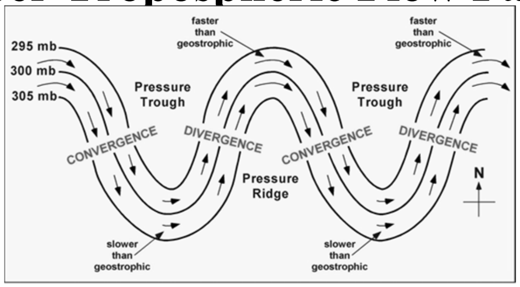
Upper Tropospheric Flow Pattern



- Upper tropospheric flows are characterized by trough (low pressure; isobars dip southward) and ridge (high pressure; isobars bulge northward).
- The winds are in gradient wind balance at the bases of the trough and ridge and are slower and faster, respectively, than the geostrophic winds.
- Therefore, convergence and divergence are created at different parts of the flow patterns, which contribute to the development of the low and high systems.

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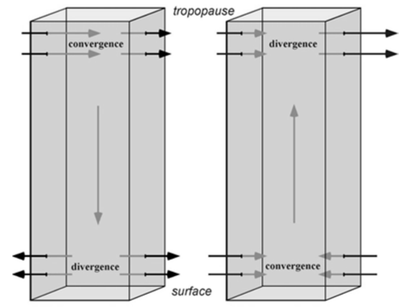
Convergence/Divergence and Vertical Motion



- Convergence in the upper tropospheric flow pattern can cause descending motion in the air column. ➔ surface pressure increase (high pressure) ➔ clear sky
- Divergence in the upper troposphric flow pattern ca cause ascending motion in the air column. ➔ surface pressure decreases (low pressure) ➔ cloudy weather

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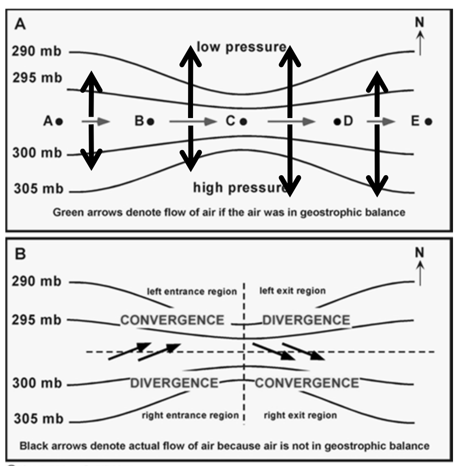
Convergence/Divergence in Jetstreak



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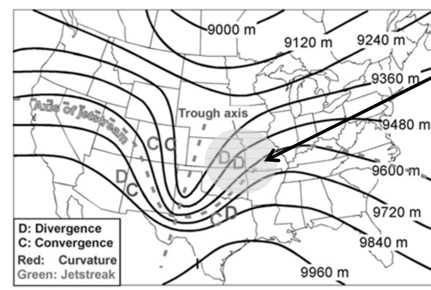
Combined Curvature and Jetstreak Effects



Surface low will develop ahead of the upper-level trough.

- The convergence/divergence produced by the curvature and jetstreak effects cancels each other to the south of the jetstream axis but enhances each other to the north of the jetsream.
- The strongest divergence aloft occurs on the northeast side of the trough, where a surface low pressure tens to develop.
- The strongest convergence aloft occurs on the northwest side of the trough, where a surface high pressure tends to develop. However, other processes are more important that this upper-level convergence in affecting the development of high pressure system.

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