MET 200 Lecture 10 Forces and Wind

Previous Lecture Precipitation

Precipitation

Warm Cloud Process

Cold Cloud Process

Types of Precipitation

Cloud seeding

The Warm Cloud Process

In summary: 3 steps in warm cloud process

1. Cooling – usually a result of lifting, and results in saturation of the air.
2. Condensation – In an environment with few cloud condensation nuclei, a few droplets can grow by condensation to the critical size where
3. Coalescence – takes over as the falling drop starts to collide and merge with smaller droplets in its path.

The Cold Cloud Process

In summary, 4 steps in the cold cloud process

1. Cooling – leading to saturation and condensation – same as warm cloud case.
2. Freezing – As cloud continues to rise, the air temperature cools enough below freezing to activate freezing nuclei within super-cooled cloud droplets (below freezing but still liquid) resulting in rapid freezing.
3. Deposition – the vapor pressure around ice crystals is less than the vapor pressure around water droplets; therefore, crystals grow rapidly at expense of remaining cloud droplets.
4. Accretion (also called riming) – comes into play when ice crystal starts falling through cloud. Ice crystals grow by collecting super-cooled droplets that freeze on contact.

MET 200 Lecture 10 Forces and Wind

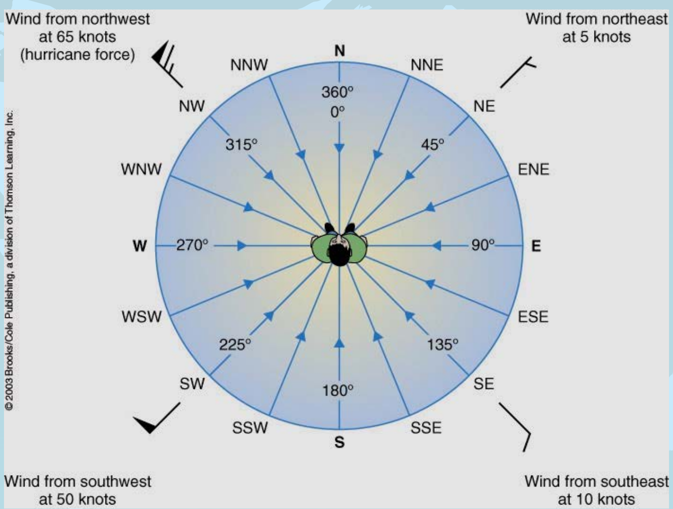

Forces, Force Balance, and Winds

Measuring Wind

Wind in the Atmosphere is measured by

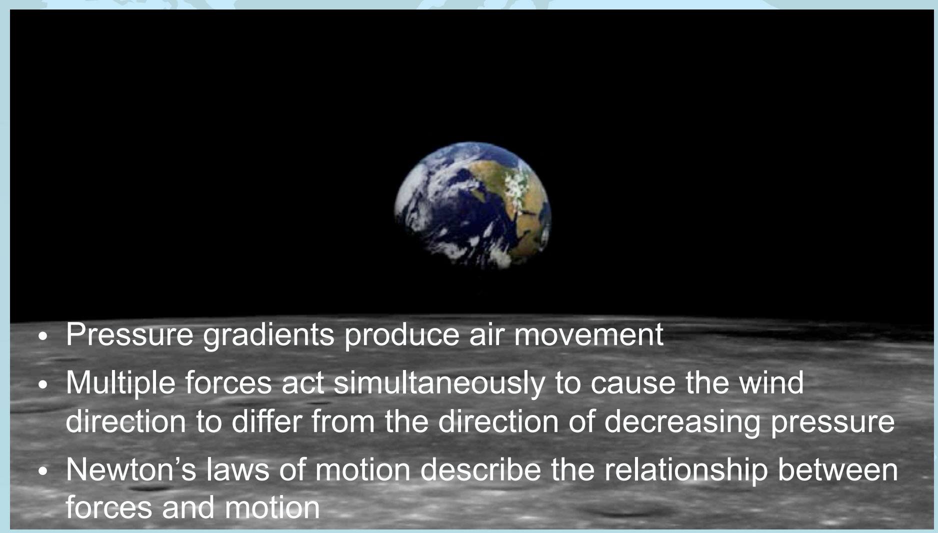
- Anemometer (10 m tower)
- Doppler Radar (rain)
- Radiosonde (balloon)
- Satellite (cloud drift)

Forces and Wind



Wind data are plotted using the convention above.

Forces and Winds



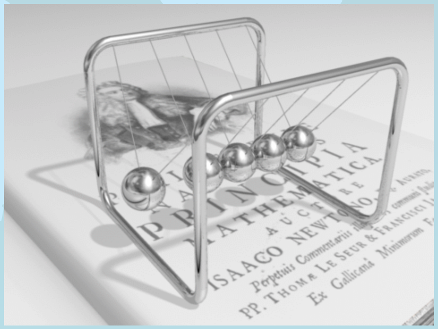
- Pressure gradients produce air movement
- Multiple forces act simultaneously to cause the wind direction to differ from the direction of decreasing pressure
- Newton's laws of motion describe the relationship between forces and motion

Forces and Wind

A force is a pushing or pulling that will result in motion if it is unopposed.

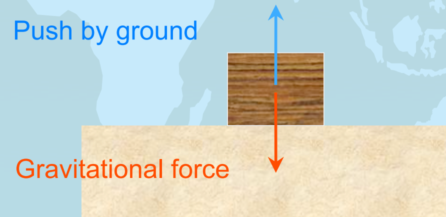
Newton's Laws of Motion

1. In the absence of forces an object at rest will remain at rest and an object in motion will remain so with the same velocity.
2. Force equals mass times acceleration (F = m·a)
3. To every action there's an equal and opposite reaction.



Forces expressed as Vectors

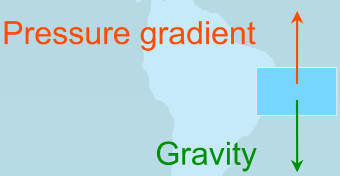
- Forces have two properties
  - Magnitude (length of arrow)
  - Direction (direction of arrow)
- Force balance

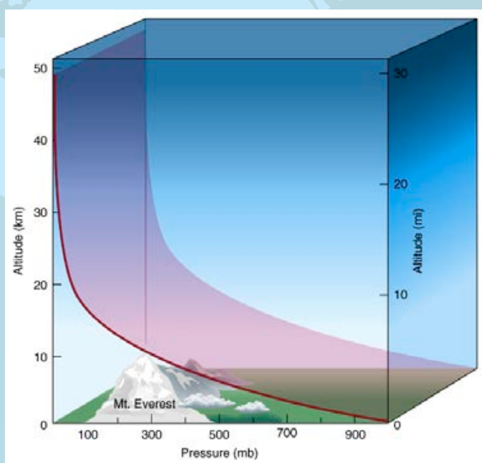


Hydrostatic Balance

What keeps air from rising due to the upward pressure gradient force?

A balance between gravity and the pressure gradient force.





Hydrostatic Equation

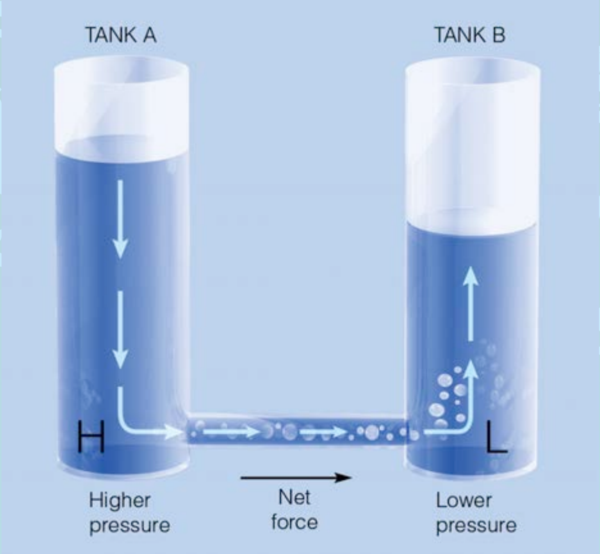
The vertical component of the momentum equation can be rewritten after elimination of small terms.

$$\frac{\partial p}{\partial z} = -\rho g$$

Since g is a constant, this equation tells us that the rate of change of pressure with height is dependent on air density or temperature: it is greater for cold dense air than for warm less dense air.

This equation is used to diagnose altitude above the ground based on the pressure distribution.

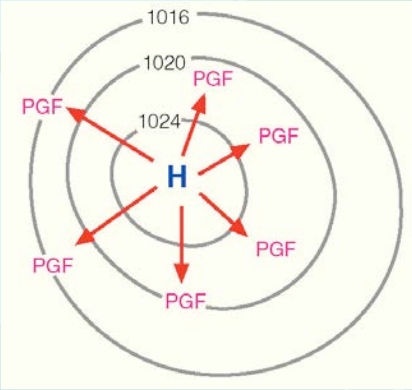
Pressure Gradient Force (PGF)



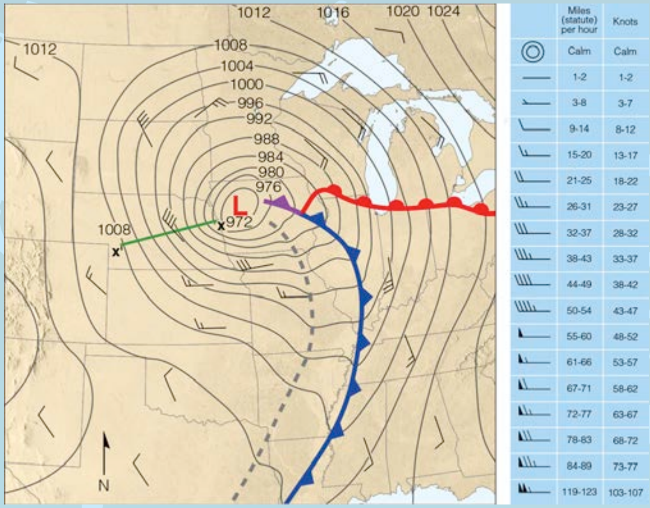
Flow (wind) driven by pressure difference.

Vector representation of pressure gradient force (PGF)

- Magnitude
  - Inversely proportional to the distance between isobars or contour lines
    - The closer together, the stronger the force
- Direction
  - Always directed toward lower pressure - perpendicular to isobars



Pressure Gradient Force (PGF)



The closer the isobar spacing, the stronger the wind

(Why doesn't the wind blow directly from high to low?)

Forces and Wind

Five Forces Affect Motions in the Atmosphere

1. Pressure Gradient — PG
2. Gravity — g
3. Coriolis — C_o
4. Centrifugal — C_e
5. Friction — F_r

Momentum Equation – Vector Form

$$\frac{D\mathbf{V}}{Dt} = -2\Omega \times \mathbf{V} - \frac{1}{\rho}\nabla p + g + F_r$$

The acceleration of the wind (LHS) is equal to the imbalance between the body forces (RHS), including Coriolis, pressure gradient, gravity and friction.

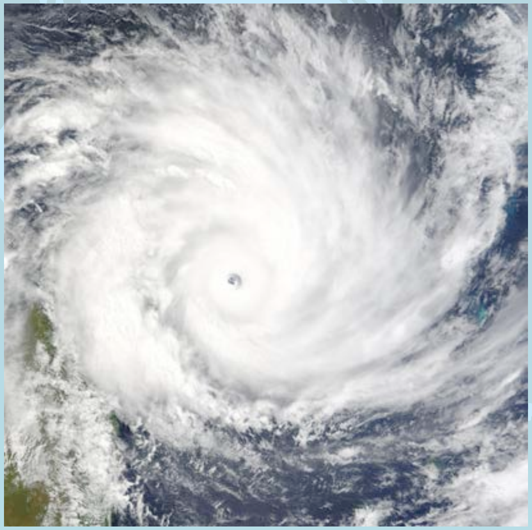
Forces and Wind

Of the five forces only two can produce winds from air that is initially at rest.

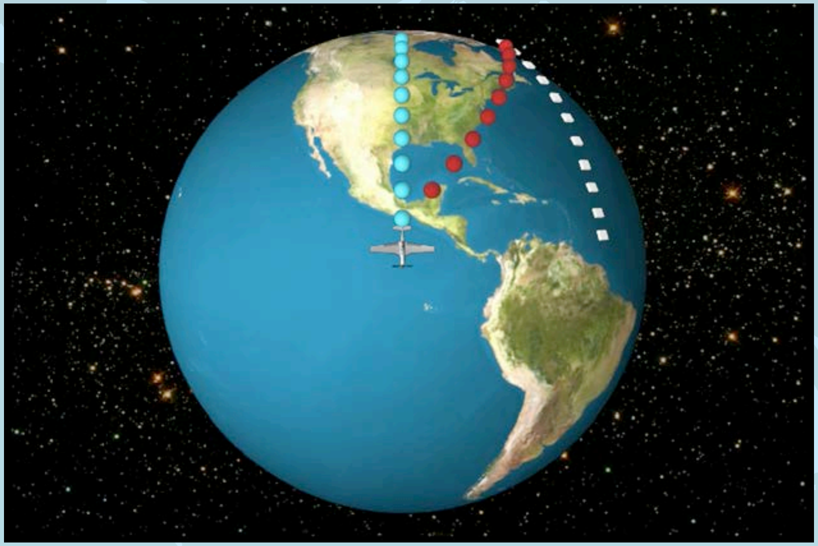
- Pressure Gradient
- Gravity

Forces controlling horizontal winds

1. Pressure Gradient Force
2. Centrifugal force
3. Coriolis Force
4. Friction



Coriolis Force

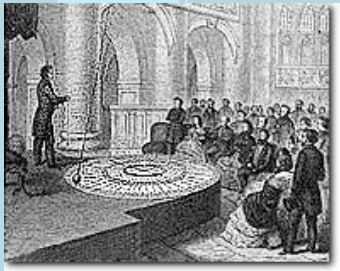


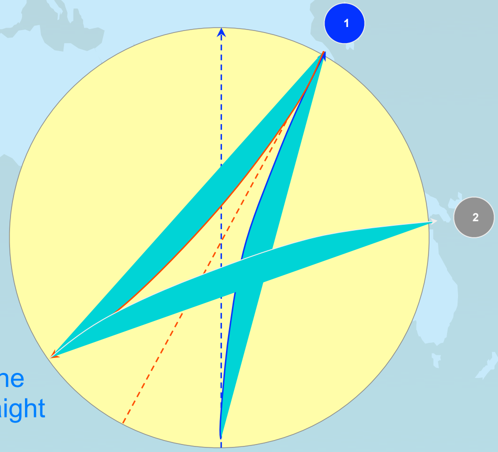
Apparent force due to rotation of the earth

The Focault's Pendulum:

Demonstration of the Coriolis Force

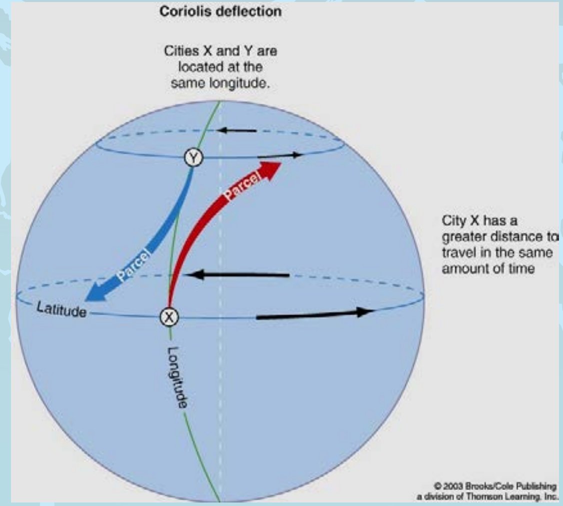
"**Come to see the Earth turn**"
Foucault's invitation of February 2, 1851





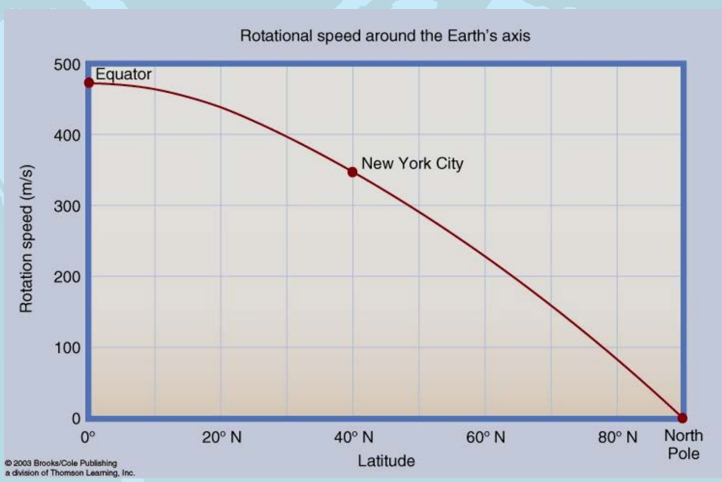
The pendulum is turned to the right of the "anticipated" straight path by the Coriolis force.

Coriolis Force



Apparent force due to rotation of the earth

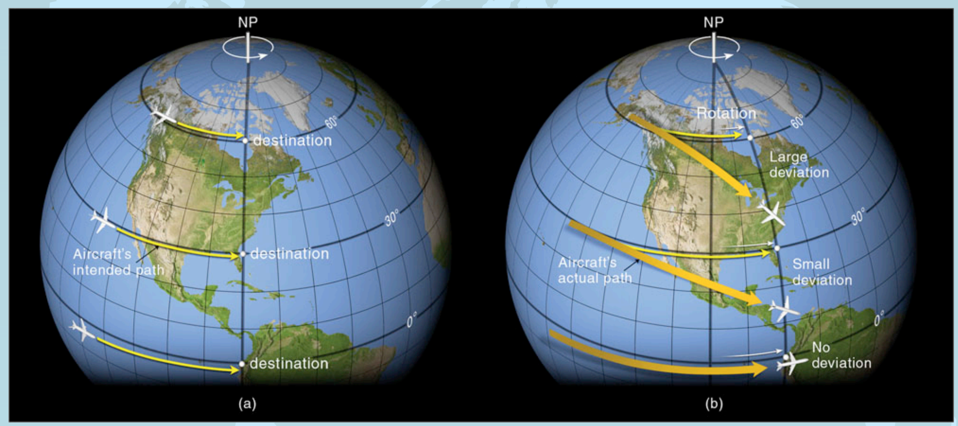
Coriolis Force



Rotation speed due to rotation of the earth

Coriolis Force

= 2 x Earth Rotation Rate x sin (latitude) x velocity



Apparent force due to rotation of the earth

Coriolis Acceleration

$$F_c = 2\Omega v \sin\phi$$

F_C = Coriolis Force

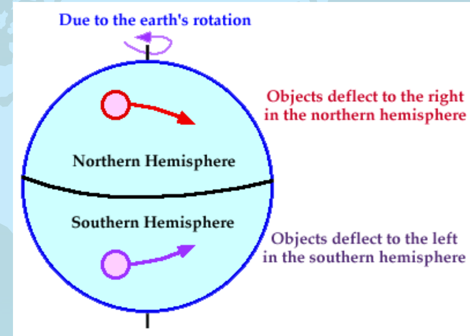
Ω = Earth rotation

v = Wind Speed

ϕ = Latitude

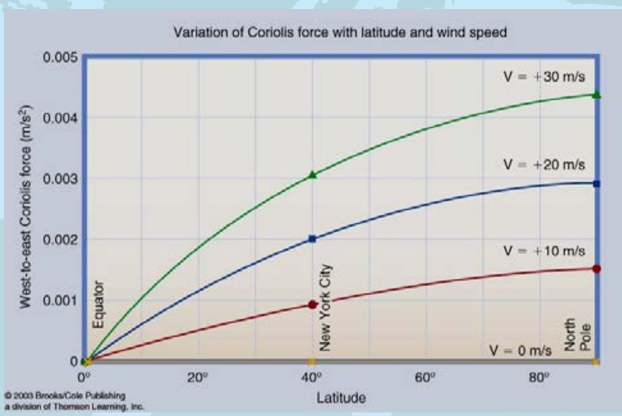
Coriolis Force

- Acts to right in Northern Hemisphere
- Stronger for faster wind
- Zero at the Equator, increasing to a maximum at the poles



Apparent force due to rotation of the earth

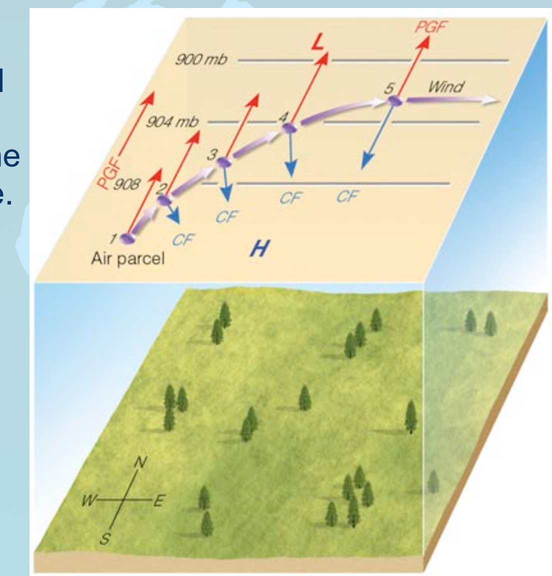
Coriolis Force



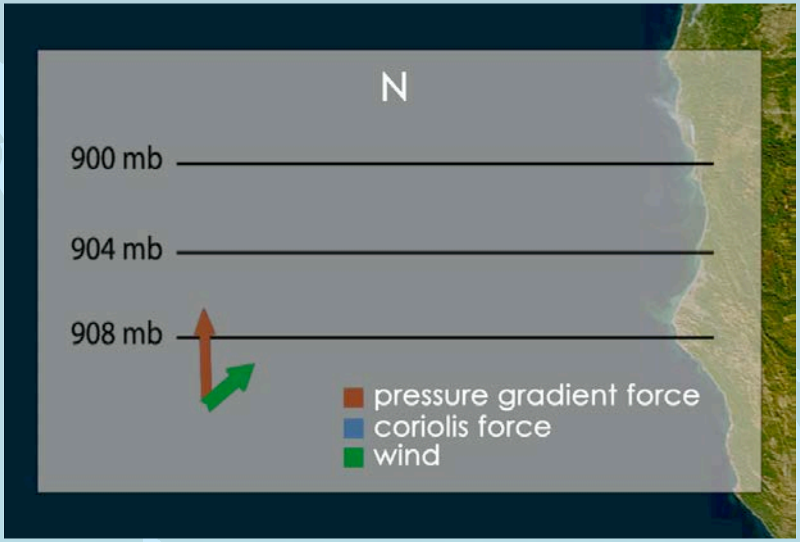
- Acts to right of the motion in Northern Hemisphere
- Stronger for faster wind
- Zero at the Equator, increasing to a maximum at the poles

Coriolis Force

Wind will accelerate until the Coriolis Force becomes as strong as the Pressure Gradient Force.



Coriolis Force



Wind will accelerate until the Coriolis Force becomes as strong as the Pressure Gradient Force.

Coriolis Force

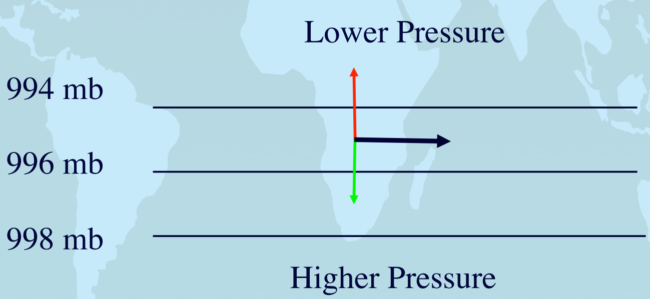
= 2 x Earth Rotation Rate x sin (latitude) x velocity

SUMMARY

- 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

Geostrophic Wind

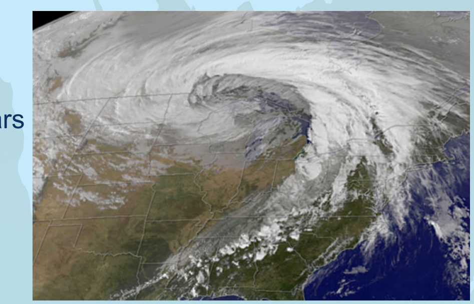
The Geostrophic wind is flow in a straight line in which the pressure gradient force balances the Coriolis force.



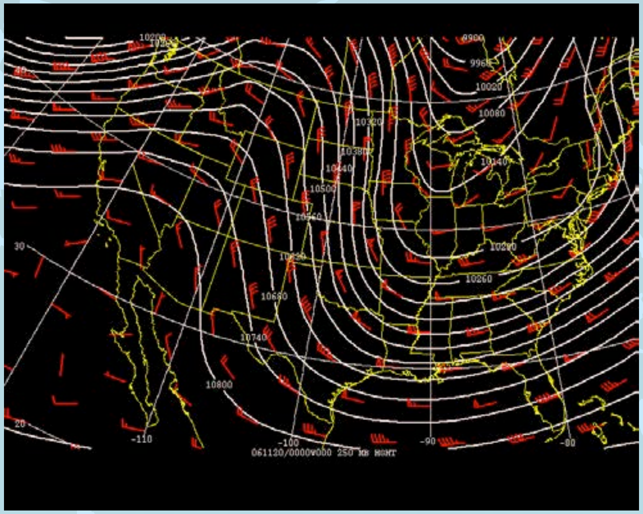
Note: Geostrophic flow is often a good approximation away from the Earth's surface.

Geostrophic Wind

- Geostrophic motion occurs when there is an exact balance between the PGF and the C_o, and the air is moving under the the action of these two forces <u>only</u>.
- It implies
  - No acceleration
    - e.g., Straight, parallel isobars
  - No other forces
    - e.g., friction
  - No vertical motion
    - e.g., no convergence



Geostrophic Wind



Note: Geostrophic flow is often a good approximation away from the Earth's surface.

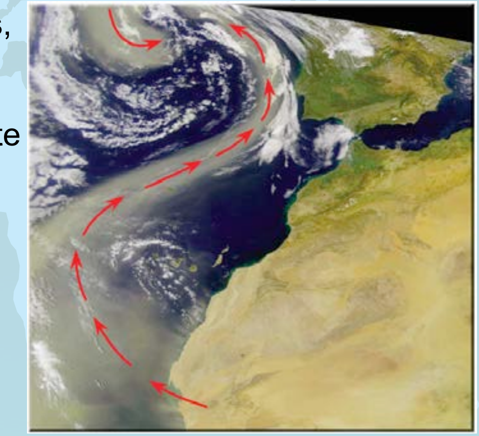
Geostrophic wind

(William Ferrel, 1856; Buys Ballot, 1857)

- Direction: in parallel to isobars, with high pressure to the right and low to the left in the Northern Hemisphere (opposite in the Southern Hemisphere)
- Magnitude: proportional to the spacing of isobars (analogous to river flow)

$fv \cong 1/\rho\ \partial P/\partial x$

$fu \cong -1/\rho\ \partial P/\partial y$



Geostrophic Wind

If we know the perpendicular distance n between isobars, we can write an equation for the geostrophic wind on a surface chart;

$$V_g = \frac{1}{\rho f} \cdot \frac{\Delta p}{\Delta n}$$

For upper level constant pressure charts we can write

$$V_g = \frac{g}{f} \left| \frac{\partial \Phi}{\partial n} \right|$$

Where Φ is geopotential height and n is distance normal to contours.

An Example

What is the Geostrophic wind speed for a pressure gradient of 2 hPa/100km and density of 1.2 kg m^{-3} at a latitude of 20° ? ($\Omega = 7.272 \times 10^{-5}$,$2\,\Omega = 1.45\text{x}10^{-4}$)

$$V_g = \frac{1}{\rho f} \cdot \frac{\Delta p}{\Delta n}$$

PGF = 2 h P_a/100 km = 200 P_a/100 km = 2 x 10^{-3} P_a/m

f = 2Ωsinθ

For 20˚ N, V_g = 2 x 10^{-3}/(1.2 x 2 x7.3x10^{-5} x 0.34) = 33.5 m/s

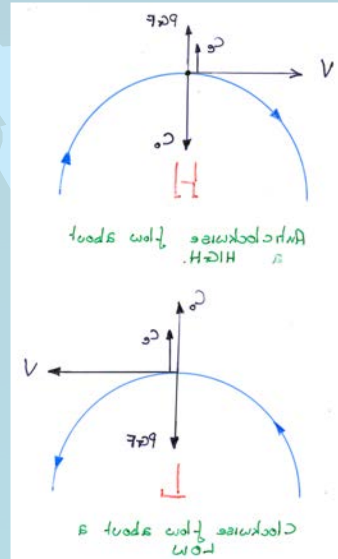
Gradient Wind – V_{gr}

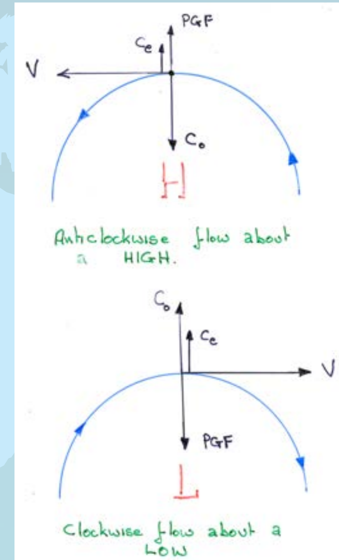
- Wind which results when the Centrifugal Force, resulting from curved flow, is exactly balanced by the Coriolis and Pressure Gradient Forces

  $C_e = PGF - C_o$

- Three Cases of V_{gr} exist
  - Anti-clockwise flow (high pressure center)
  - Clockwise flow (low pressure center)
  - Straight Flow ($V_{gr} = V_g$ which is a special case)

Northern Hemisphere　　Southern Hemisphere





Note mirror image nature of force balance across the equator.

Gradient Wind Equation

$$\frac{V^2}{r} = \frac{1}{\rho}\left|\frac{\partial p}{\partial n}\right| - |f|V$$

The previous slide shows us the balance of forces required to make Gradient flow occur.

Gradient flow around a cyclone is sub-geostrophic, and that gradient flow around an anti-cyclone is super-geostrophic.

Gradient Wind Equations

The equations for the gradient wind (V_{gr}) depend on whether the flow is cyclonic or anti-cyclonic. Here V_g is the geostrophic wind and r the radius of curvature. Solving the quadratic equation for V on the last slide we have:

Cyclonic Flow $$V_{gr} = -rf + \sqrt{\frac{r^2 f^2 + 4 r f V_g}{2}}$$

Anticyclonic Flow $$V_{gr} = rf - \sqrt{\frac{r^2 f^2 - 4 r f V_g}{2}}$$

Gradient Wind

There are some limiting factors to gradient flow around high pressure systems when we look at the equation closely.

$$V_{gr} = \frac{r\,f - \sqrt{r^2 f^2 - 4\,r\,f\,v_g}}{2}$$

There is a maximum value to V_{gr} when $\sqrt{(\ )} = 0$

i.e. when $r^2 f^2 = 4\,r\,f\,v_g$

$$\therefore\ v_g = \frac{r^2 f^2}{4\,r\,f} = \frac{r\,f}{4}$$

Substituting back into the original equation we have

$$V_{gr\,max} = 2V_g$$

Gradient Wind

This tells us that there is a limit to how fast the wind can move around an anti-cyclone, and that limit is twice the speed of the Geostrophic wind.

There is no limit to the speed a cyclonic circulation can achieve.

Gradient Wind

For the equation to make sense for the anticyclonic case, the number inside the bracket must be ≥0.

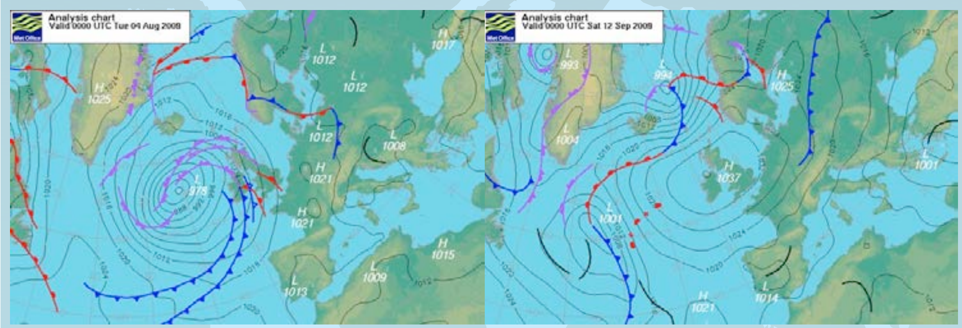
$$\therefore\ r^2 f^2 > 4\,r\,f\,v_g$$

$$> 4\,r\,f\left(\frac{1}{\rho\,f}\cdot\frac{\partial p}{\partial n}\right)$$

$$> \frac{4\,r}{\rho}\cdot\frac{\partial p}{\partial n}$$

$$\therefore\ \frac{\rho\,r\,f^2}{4} > \frac{\partial p}{\partial n}$$

Gradient Wind



This tells us that when the radius of curvature is small, then so must be the pressure gradient.

In other words the isobars must get further apart the closer you get towards the centre of the anticyclone.

There is no limit to the spacing of the isobars around the centre of cyclonic flow.

Cyclostrophic Flow

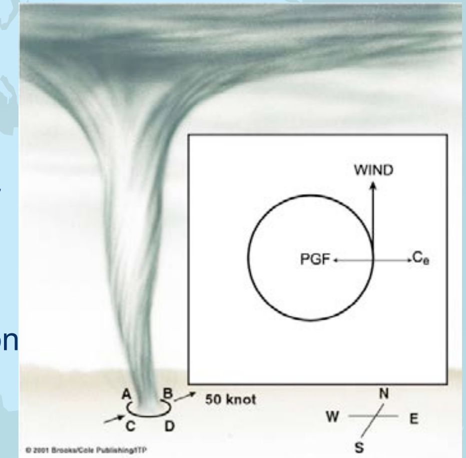
As mentioned previously there are no restrictions to the strength of the pressure gradient around low pressure systems. This can lead to situations whereby if the radius of curvature is very small (such as found around tornadoes), then the centrifugal force and pressure gradient forces balance each other. This limiting case is called Cyclostrophic flow.

Bad hair day

Centrifugal Force

= velocity^2 / radius

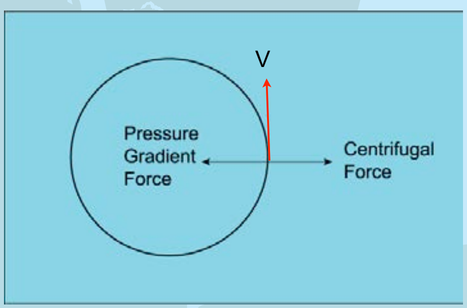
- Magnitude
  - depends upon the radius of curvature of the curved path taken by the air parcel
  - depends upon the speed^2 of the air parcel
- Direction
  - at right angles to the direction of movement

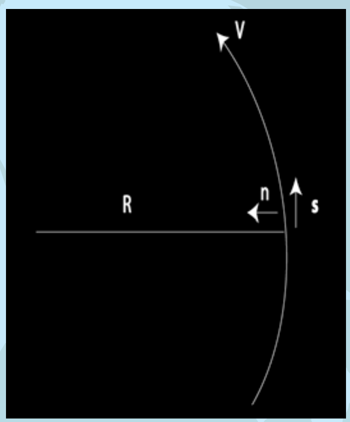


Cyclostrophic Wind

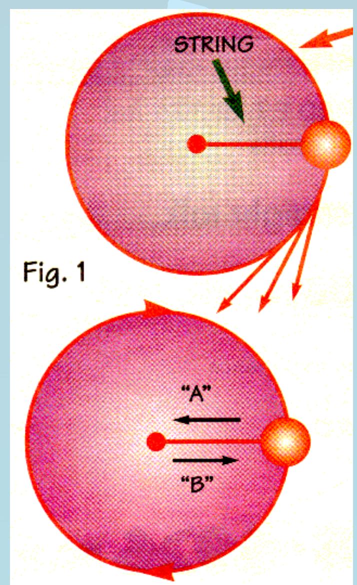
$$V^2/R = -(1/\rho)(dp/dn)$$

$$V = ((-R/\rho)(dp/dn))^{1/2}$$





Centrifugal Force

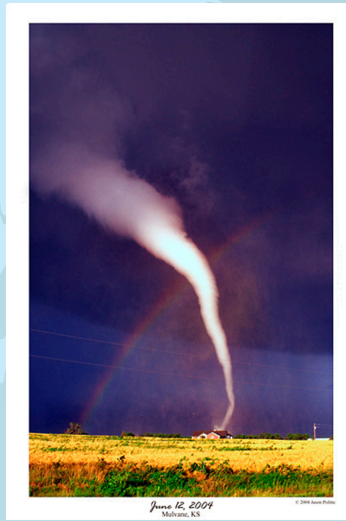


- When viewed from a fixed reference frame, a ball swung on a string accelerates towards to center of rotation (centripetal acceleration).
- When viewed from a rotating reference frame, this inward acceleration (caused by the string pulling on the ball) is opposed by an apparent force (centrifugal force).
- Centripetal and centrifugal forces are equal and opposite.

Centrifugal Force

Examples of Centrifugal Force in action
- Planets orbiting the Sun.
- Satellites orbiting the Earth.
- Merry-go-round
- Tether ball
- Golf swing
- Etc.

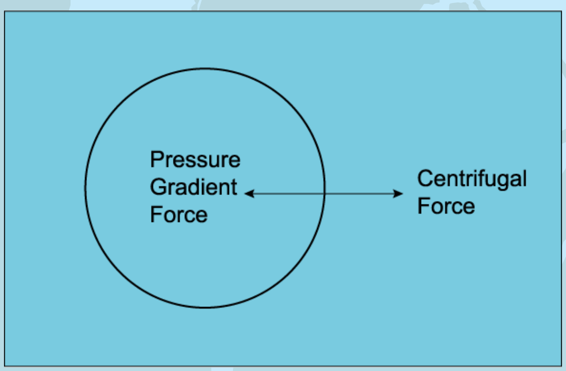
In the atmosphere any curved flow experiences a centrifugal force.



Centrifugal Force

- Magnitude
  - depends upon the radius of curvature of the curved path taken by the air parcel
  - depends upon the speed^2 of the air parcel
- Direction
  - at right angles to the direction of movement

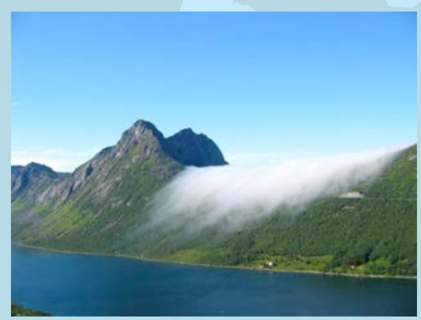
CYCLOSTROPHIC BALANCE



Occurs in:
- Hurricane eye-wall
- Tornados
- Water spouts
- Dust devils

Friction

- Air in contact with the surface experiences frictional drag, effectively slowing the wind speeds.
- Planetary Boundary Layer (PBL) – the lowest ~1.5 km of the atmosphere which experiences friction.
- Free Atmosphere – the remaining atmosphere which is free from frictional effects above the PBL.



Friction is important near Earth's surface

Frictional drag near the Earth's surface slows wind down

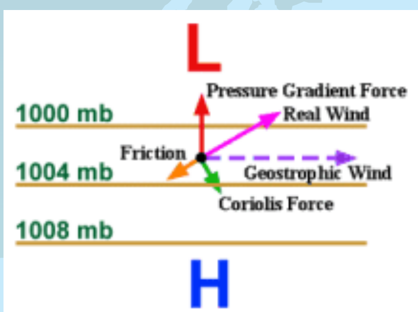
- Magnitude
  - Depends upon the speed of the air parcel
  - Depends upon the roughness of the terrain
- Direction
  - Always acts in the direction opposite to the movement of the air parcel
- Important in the lowest ~1500 m of the atmosphere called the planetary boundary layer.

What happens when we add friction?

If the wind speed is reduced by friction, the Coriolis force will decrease and will not quite balance the pressure gradient force

- Force imbalance (PGF > C_oF) pushes wind toward low pressure
- Angle at which wind crosses isobars depends on surface roughness
  - Average ~ 30 degrees over forested land
  - Average ~ 10 degrees over the ocean

Geostrophic wind plus friction

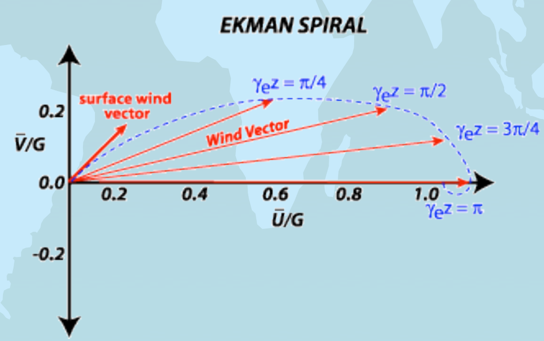


The wind no longer blows parallel to the isobars, but is deflected toward lower pressure; this happens close to the ground where terrain and vegetation provide friction

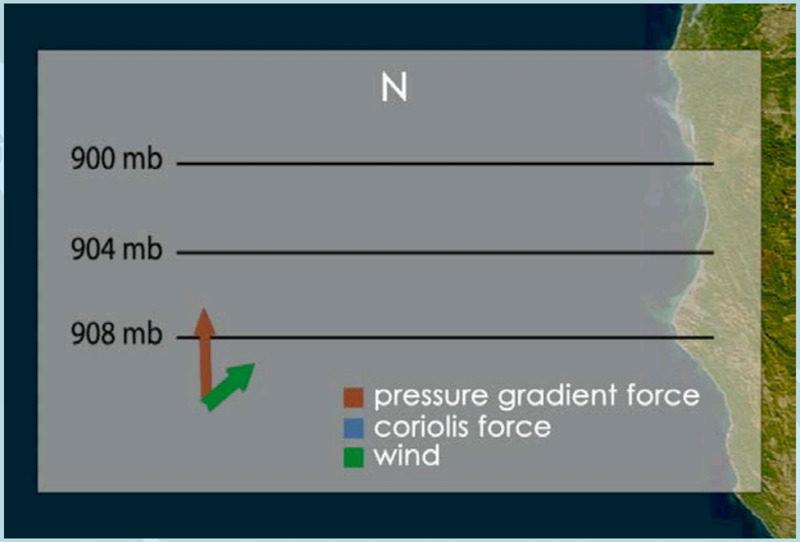
http://ProfHorn.meteor.wisc.edu/wxwise/kinematics/testwind.html

Effect of Friction – Ekman Spiral

- Friction is strongest near the ground.
- Stronger friction means the air crosses isobars at a greater angle.
- Thus as a weather balloon rises in the boundary (friction) layer, the wind (balloon) direction will turn.

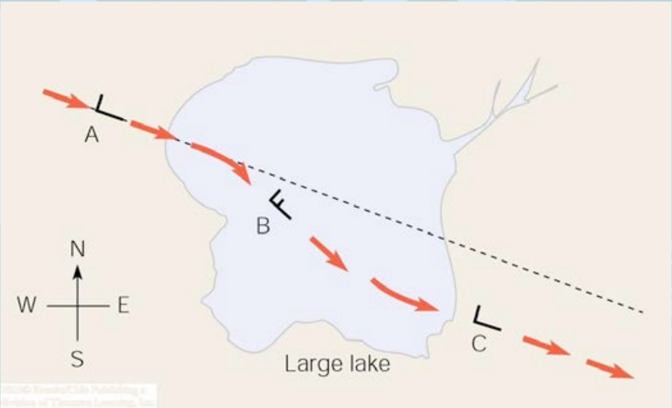


Friction and Coriolis Force



As a weather balloon rises in the boundary (friction) layer, the wind (balloon) direction will turn.

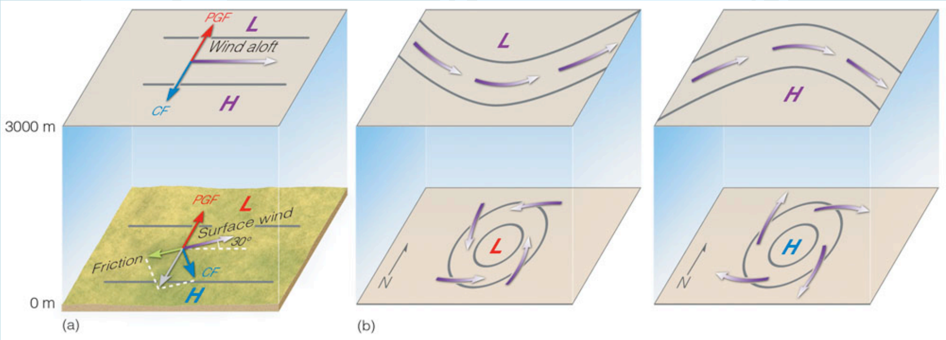
Effect of Friction – Convergence



Differing friction cause divergence between A and B and convergence between B and C.

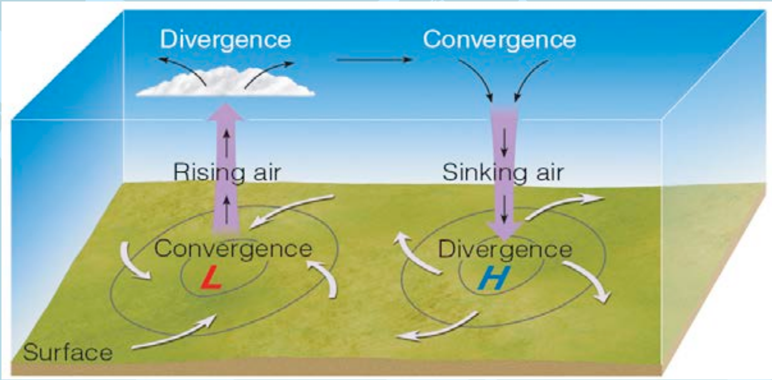
http://ww2010.atmos.uiuc.edu/(Gl)/guides/mtr/fw/bndy.rxml

Effect of Friction



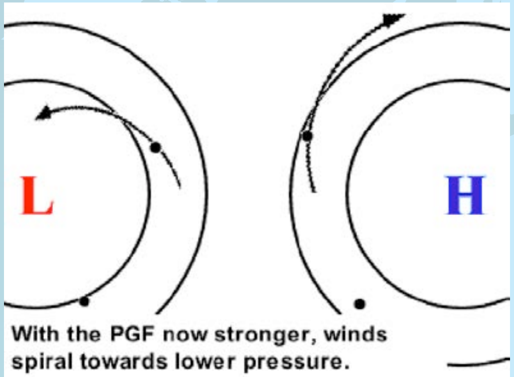
Friction causes low level convergence into lows and divergence out of highs.

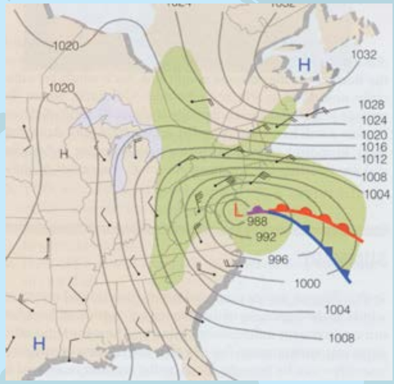
Winds and vertical air motion



- Surface winds spiral
  - Counterclockwise in toward center of low pressure (convergence)
  - Clockwise 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

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

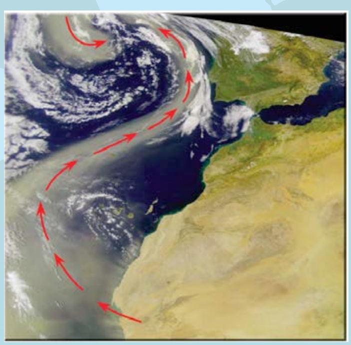
Review of Forces

1. Pressure Gradient Force* – changes in pressure over a distance causes air to move.
2. Gravity* – only acts in the vertical direction
3. Coriolis Force – due to Earth's rotation underneath the moving air.
4. Centrifugal Force – whenever there is curved flow (curved isobars)
5. Friction – only important near the Earth's surface

* Only the pressure gradient force and gravity can cause winds in air that is initially at rest.

Balance of Forces

- Cyclostrophic Balance – Pressure Gradient Force = Centrifugal Force
- Geostrophic Balance – Pressure Gradient Force = Coriolis Force
- Gradient Wind Balance – Pressure Gradient Force = Centrifugal + Coriolis Forces
- Hydrostatic Balance – Pressure Gradient Force = Gravity



Questions?