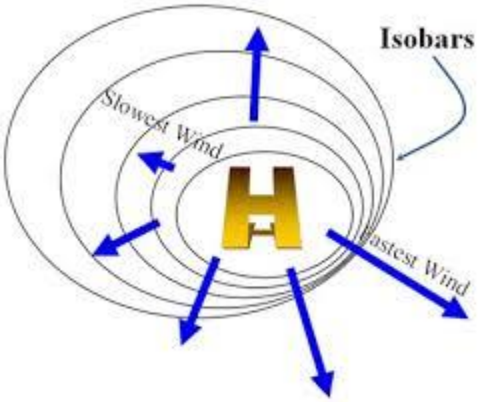
IX. GEOSTROPHIC WINDS

A. Here, we'll examine forces that work counter to nature's tendency to push air high to low pressure, from colder places (the north) to warmer places (the south).
   1. The 4 principal forces that determine where, when, and how quickly the horizontal wind blows are pressure gradient force (PGF), the Coriolis force, frictional force, and a centripetal or centrifugal force.

B. A **pressure gradient** is a pressure difference divided by a distance.
   1) Pressure differences drive winds, but pressure gradients determine wind speed.
   2) The pressure gradient is large when the pressure difference is large, or the distance between the 2 are small.



      a. Average sea level pressure is about 1000 mb. What would a large pressure difference be?
         i) How about 10%? So 10% would 100 mb.
         ii) Let's picture a 100 mb pressure difference between 2 places.
         iii) What kind of wind would this pressure difference produce? It depends on the distance.
         iv) If the 2 locations were separated by the entire hemisphere, the wind would by very weak. The pressure difference is large, but the distance is enormous, and the pressure gradient is small.
         v) That same pressure difference of 100 mb over a distance of only a mile or 2 would generate the enormous winds of the EF5 tornado, the strongest winds on Earth.
   3) Temperature differences make pressure differences, and pressure differences drive winds.
      a. We saw this was true in the case of the sea and land breezed, circulations that are established owing to temperature differences across a coastline.
         i) There are a lot of reasons why one place might be warmer than another.
         ii) It might receive more solar radiation, owing the Earth's sphericity and tilt.
         iii) It might receive more infrared radiation from the atmosphere, owing to a greater concentration of greenhouse gases, especially water vapor, and the presence of low clouds.

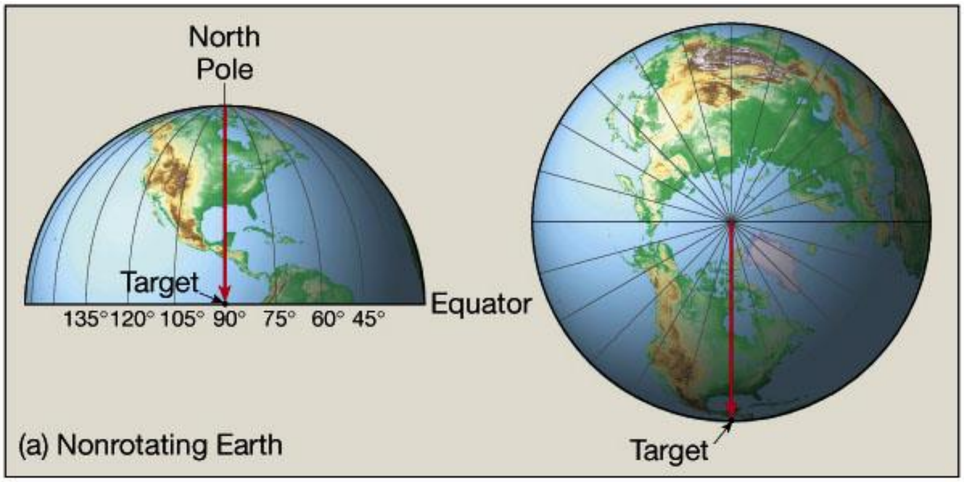
        - iv) It might absorb more of the radiation it does receive because of the characteristics of its surface.
        - v) If might not be able to resist the radiation it does absorb, owing to a low thermal inertia.
        - vi) It might experience more subsidence, descending motion, increasing the temperature by compression warming.
        - vii) More water vapor may be condensing there, liberating latent heat.
    - b. Nature wants to push air from high to low pressure.
        - i) Where there's more mass piled up, the pressure is higher, at least at the surface, and Nature wants to push that air away, towards a place of relative deficit, having a lower pressure.
        - ii) These 2 combinations help to explain the sea breeze, as well as the land breeze, examples of what we called **thermally direct circulations**. But both are also part of a circulation that has surface winds, blowing from colder to a warmer place.

C. Our second force is the Coriolis force, or Coriolis effect, which exists owing to earth's rotation.

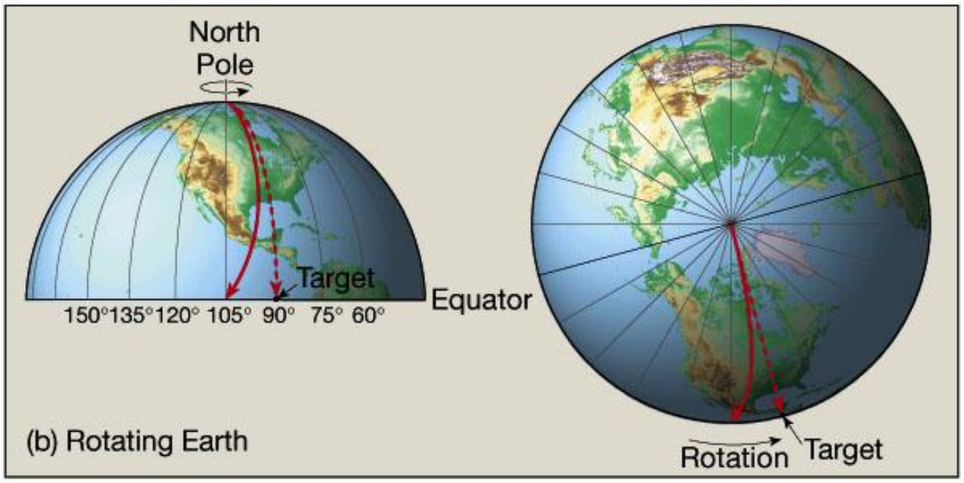
- 1) Newton's first law and Coriolis circles:
    - a. Newton's first law of motion presents a simple yet very powerful constraint on motions.
        - i) It states that an object, once put into motion, continues moving in a straight line and at constant speed. . . unless other forces are acting.
        - ii) Can an object once propelled subsequently change direction? Yes, if some force appears to accomplish that.
        - iii) By that same token, if we see something curve, then it follows there must be a force impelling this deviation from straight-line motion.
        - iv) Note this well: if we see something curve, we have to explain the curvature. We have to identify a force.
- 2) Consider a rocket put into motion on the rotating Earth.
    - a. We are observers located on that spinning sphere.
    - b. Once launched, we see the rocket start curving, and we give the force causing that curvature a name: **the Coriolis force**.
    - c. That Coriolis force is acting to the object's right, following its motion, in the Northern Hemisphere.
    - d. Thus, if we launch the rocket northward, it cannot continue traveling due north.
    - e. Instead, we see it start curving eastward, the direction to the object's right. The deflection does not stop there.
    - f. Once eastbound, the Coriolis force works to bend the object to the south.
    - g. Once southbound, Coriolis encourages a westward deflection. Finally, the westbound rocket starts curving towards the north, the direction we wanted it to travel in the first place.
    - h. The object is has begun describing CW circles, called Coriolis or inertial circles.
- 3) In the section 2) above, the operative words are we see.

   a. From our point of view, the rocket constantly deviates from straight-line motion. Since we see curvature, there must be a force, and we dub this the Coriolis force.
   b. This all makes sense from our point of view, because it explains what we see.
   c. However, the rocket didn't actually curve at all.
   d. The rocket was launched and allowed the go on its merry way. No other forces have actually intervened.
   e. Thus, the rocket went straight, as Newton's first law insisted it must. Yet, we saw it curve – and we blamed the deflection on the Coriolis force.
   f. How can we see a rocket curve when in actual fact it went straight? There is only one answer: if the rocket didn't turn, we did!

4) Layton, Utah is directly north of Cabo San Lucas, Mexico , as indicated in Figure below.



(a) Nonrotating Earth

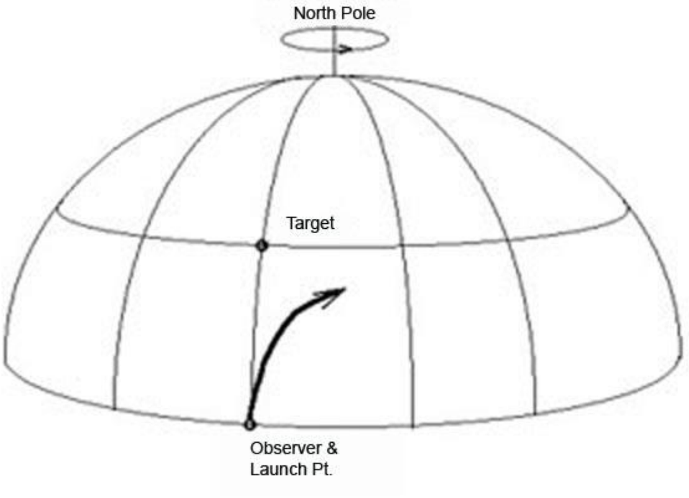


(b) Rotating Earth

   a. That's true morning, noon and night.
   b. What's more, the relative positions of those two cities never changes – at least that's what we see.
   c. However, that's not the view seen from space, a Point of view looking down on the Earth. Not if the Earth is rotating, that is.

d. Consider first a nonrotating Earth.
    i) If you launch a rocket from Cabos San Lucas to Layton, and just let it go, no other real forces influencing its trajectory in the horizontal plane intervene.
    ii) The rocket goes straight, and finds its target.
    iii) Because we are not rotating, we also see the rocket go straight. It travels due north.

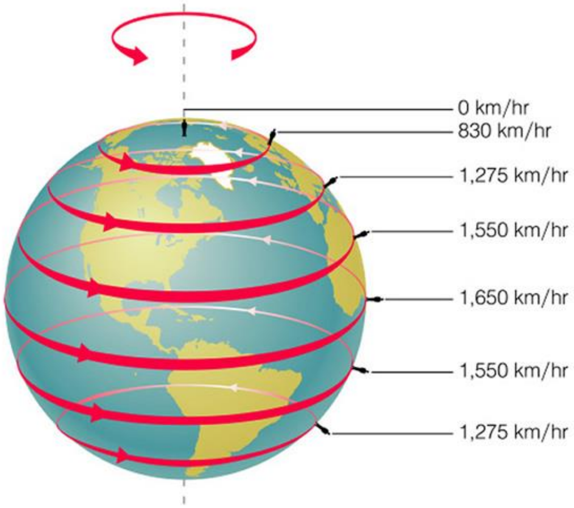
e. Yet, on a rotating Earth, what we call "north" is constantly changing – at least as seen from space.
    i) The Figure below depicts the relationship between our two cities as seen from above, both now and a few hours from now.



    ii) The Earth is rotating counterclockwise (CCW) from this viewpoint, and both Layton and Cabo San Lucas are being carried eastward.
    iii) On a rotating Earth, the rocket still travels straight after launch. The rocket appeared to curve to our right because we ourselves turned CCW along with the Earth.
    iv) The upshot is that a rocket, once launched in a particular direction, cannot continue moving in that direction by itself . It would require nudging and guidance – additional forces – to compensate for the Earth's spin.
    v) Indeed, without such guidance, we cannot fire a rocket from the equator and have it ever reach the pole.
    vi) In the absence of other forces, the rocket would continue making endless inertial circles, effectively getting nowhere.
    vii) From our point of view, the rocket is turning; from its perspective, we're the ones who are turning.
    viii) No matter. The rocket doesn't reach the pole.

5) Key points regarding the Coriolis force (applicable to Northern Hemisphere):
    a. It acts any object (air parcel, missile, train) moving over an appreciable distance (100-200 mi or so) on the Earth. Thus, it does not act the sea-breeze, tornadoes, pitched baseballs and water owing down the kitchen sink.

b. It attempts to force objects to curve to the right following its motion in the Northern Hemisphere. (However, whether objects do curve rightward depends on whether other forces are acting.)
c. It is proportional to object speed - and does not act stationary objects.
d. It exists due to the Earth's rotation, and NOT because the Earth turns beneath moving objects.
e. Every object on Earth spins because the Earth does.
f. An object's spin rate depends on its distance from spin axis (i.e., it's latitude; see Figure below).

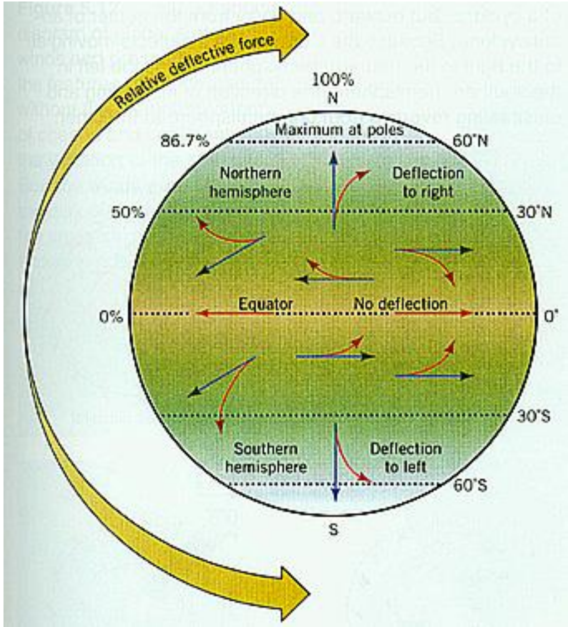


    i) Equatorial objects spin fastest since they're farthest from spin axis.
    ii) This spin gives the object angular momentum, which is conserved as it moves on the Earth.
    iii) Momentum = mass x velocity.
    iv) Angular momentum = momentum in a circular path of a given radius.
    v) Thus angular momentum = mass x spin velocity x radius
    vi) If you decrease (increase) an object's radius of spin, its rate of spin increases (decreases) [Think of a figure skater]
    vii) To decrease an object's spin radius, move it to the north, closer to spin axis -its spin rate must increase.
    viii) To increase an object's spin radius, move it to the south, farther from the spin axis - its spin rate must decrease.
    ix) This is necessary so the object's angular momentum stays same.

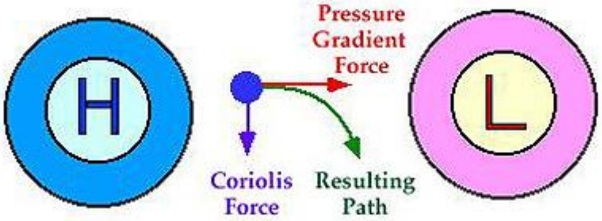
g. Example in point:
    i) Start with object located at latitude of Layton (42° North Latitude).
    ii) Move object to the south, it moves away from the spin axis.
    iii) This increases its radius and decreases its spin velocity.
    iv) However, at the same time, the spin velocity of ground beneath is increasing as it moves southward, towards equator.
    v) Object cannot keep up with the increasing spin rate below.

            - vi) Therefore, object curves westward, against the Earth's spin direction, thereby reducing its spin relative to the Earth below the object. Curving tendency is to object's right.
            - vii) Object continues to curve right as it tries to return to its original latitude (42° N Latitude). Soon, it starts heading northward (but still curving to its right).
            - viii) It overshoots original latitude because it still has an acceleration. This carries the object north of its original latitude, where the Earth has less spin velocity than the object. Meanwhile, object's distance from spin axis decreases, thus increasing its spin velocity.
            - ix) Object, now with excess spin, bends eastward towards the Earth's spin direction, increasing the object's spin velocity relative to the solid Earth below. Note, however, that the object is still curving to its right.
            - x) Object continues curving rightward and eventually starts moving towards the south and again reaches its original latitude. The object may continue in an endless loop, called an inertial or Coriolis circle. This explains the principal ocean currents.
            - xi) Minor, unimportant point: The circle isn't actually a perfect circle (as shown) because of the sphericity of the Earth. If the Earth were flat, it would be a perfect circle.
        - h. Final note: candidly, there is something missing from this story. The rightward curvature owing to the northward and southward displacements has been adequately explained using angular momentum conservation, but we actually need a better explanation for why eastbound objects curve south and the northward direction of westbound objects.
- 6) Why does the Coriolis force act to the left, following the motion in the Southern Hemisphere? An why does this force vanish at the equator?
    - a. Seen from above the North Pole, the Northern Hemisphere turns counterclockwise.
    - b. Seen from above the South Pole, the Southern Hemisphere turns clockwise.
    - c. The Coriolis force acts to the left, following the motion in the Southern Hemisphere.
    - d. To answer the question of why the Coriolis force vanishes at the equator, let’s consider vectors. [A vector is an arrow that represents a path and can be broken down into it’s components]
        - i) Think of a spin axis of the Earth as a vector whose orientation is determined by the right-hand rule.

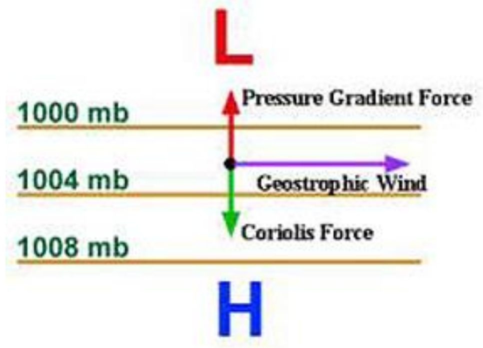
        ii) From the North Pole, the Earth’s spin axis is straight up and down; it’s in the local vertical.
        iii) As we move toward the equator, the vertical component of the spin axis becomes smaller.
        iv) The Earth is still spinning, but less of that spin is working to rotate the coordinate system at that latitude.
        v) The Coriolis force represents the spin vector in the local vertical.
        vi) At the equator, the Earth’s spin axis is actually horizontal relative to the ground. The vertical component of the spin axis is zero, so the Coriolis force vanishes at the equator. The Earth spins, but north does not.



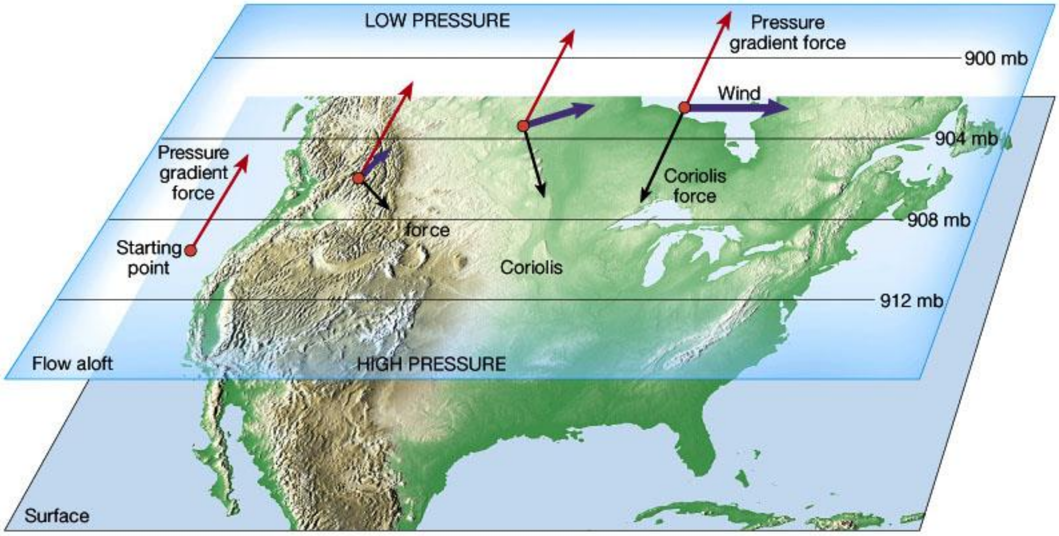
7) For the large-scale wind that wants or needs to travel a considerable distance at moderate speed, the 2 most important forces are pressure gradient force and Coriolis.
    a. The wind that results when both pressure gradient and Coriolis force are active (active against each other) is called the **geostrophic wind**.
    b. This is the wind balance that is created because the Earth turns.
    c. Consider a pressure difference between 2 isobars and an air parcel.
        i) The parcel experiences a pressure gradient force directed toward low pressure.
        ii) Once it begins to move, the Coriolis force appears, directed to the right.
        iii) The combination of these 2 forces causes the parcel to deviate to the right of its original path.



    iv) The Coriolis force continues to turn the parcel to the right until the pressure gradient force and the Coriolis force are locked in opposition.
    v) In this situation, the wind is blowing parallel to the isobars with low pressure to the left. This is **geostrophic balance**.



    vi) The wind is not moving toward low pressure, the direction the pressure gradient force is trying to push it.
    vii) The wind is not turning to the right, following the motion, as the Coriolis force is trying to push it.
    viii) Instead, it's a straight-line wind.
    ix) We cannot disturb the geostrophic balance by pushing large-scale wind harder.
    x) Ultimately, the pressure gradient force determines the wind speed, but the Coriolis fore is proportional to wind speed.

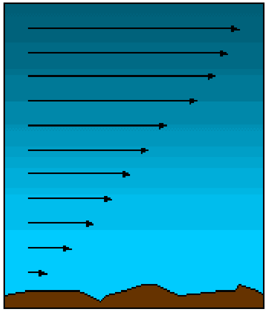


    xi) At sea level, if the wind is geostrophic, we usually know that it's blowing with low pressure to the left. Its speed will increase as the isobar spacing on a sea level pressure chart becomes smaller.

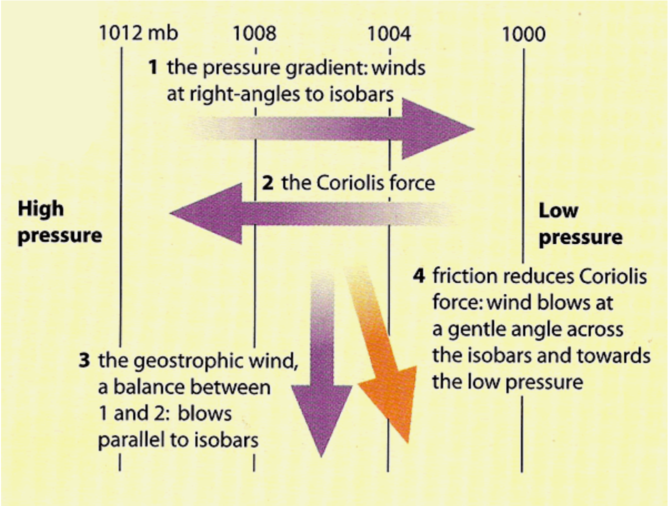
d. The geostrophic wind blows parallel to, not across, isobars.
    i) But isobars are not always straight, and to make air flow parallel to curving isobars, we need to add another force to the mix.
    ii) Sometimes, we can make air blow across isobars from high to low pressure, but that requires another force.

D. Let’s begin with the third force, **friction**.

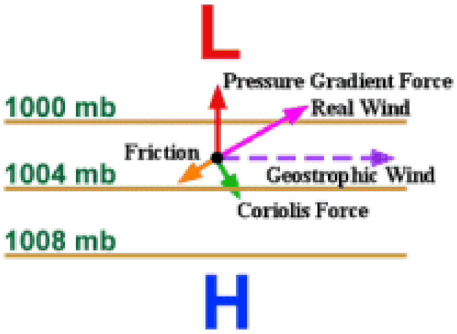
  1. The Earth’s rotation, through its proxy, the Coriolis force, turns large-scale winds so that they blow perpendicular to the pressure gradient, with low pressure to the left in the Northern Hemisphere.
  2. Friction acting near the earth’s surface to reduce wind speeds, disturbs the geostrophic balance so that the large-scale wind will blow toward low pressure.



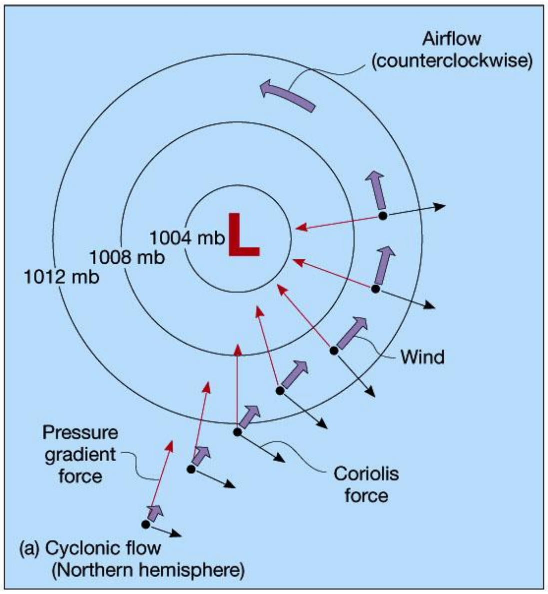
    a. Friction weakens the Coriolis force.
    b. On the image below, we see the wind blowing from low pressure to the right and Coriolis acting to the left of the motion.
    c. Friction opposes the motion, causing it to slow.
    d. The pressure gradient force is then able to pull the air toward low pressure, at least at a shallow angle.



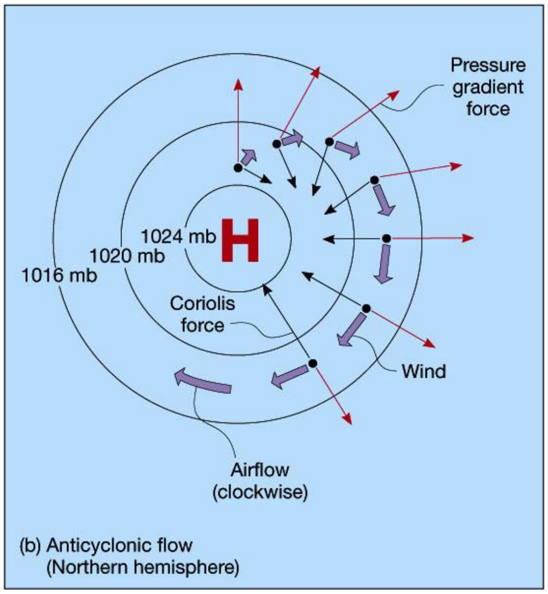
    e. The result is a 3 way balance of forces in which air can move across isobars, toward lower pressure.



3. Now, let’s consider a different 3-force balance.
   a. Wind tends to turn counterclockwise around large-scale regions of low pressure in the Northern Hemisphere and clockwise around highs.
   b. These lows and highs are called **cyclones and anticyclones**.



(a) Cyclonic flow
(Northern hemisphere)

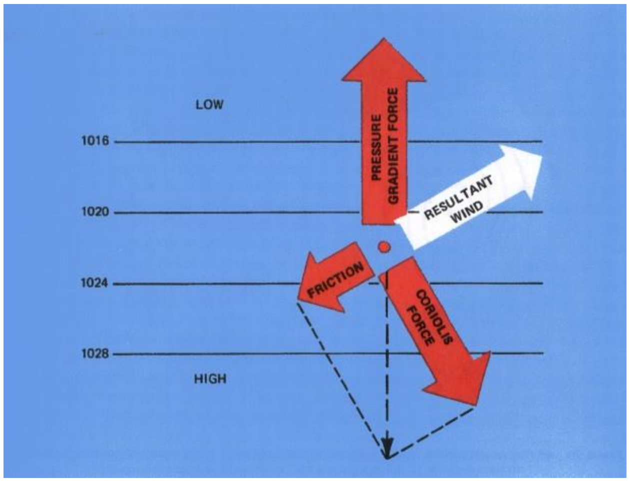


(b) Anticyclonic flow
(Northern hemisphere)

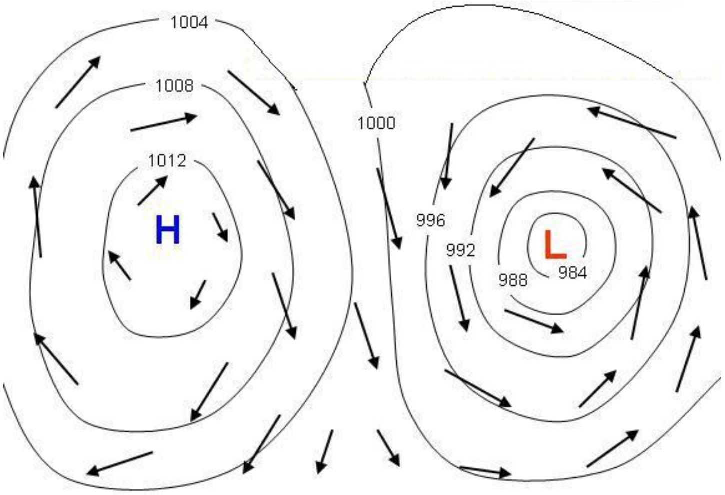
   c. Note that the air flow is parallel to isobars of pressure. This means that friction is absent.
   d. The winds’ change of direction is usually explained as a centripetal or centrifugal force, depending on one’ point of view.
   e. The combination of pressure gradient force, coriolis, and centripetal or centrifugal forces is called **gradient wind balance**.
   f. Centrifugal and centripetal forces exist when there is spin.
      i) Centrifugal force is directed outward from the center of spin.
      ii) Centripetal force is directed inward toward the center of spin.
   g. Starting at geostrophic balance, the centripetal force acts in the direction of either the pressure gradient force, guiding the air around the low, or the Coriolis force, guiding the air around the high.
   h. Where did the centripetal or centrifugal force come from?
   i. Starting again with geostrophic balance, suppose an air parcel’s path takes it toward a place where the isobars are curving in a **counterclockwise** fashion.
      i) Inertia acts to push the air on a straight path, but notice that this would carry the air across the isobar toward higher pressure.
      ii) Notice that the pressure gradient force, which points most directly toward low pressure, opposes inertia.
      iii) Part of the wind’s driving force is directed against the parcel, and the air must slow down.
      iv) When the air slows down, the Coriolis force is reduced, allowing the pressure gradient force to change the direction of the air, except this time, it doesn’t result in cross-isobar flow.
      v) Instead, the parcel continues to follow the isobars as they curve.

        vi) Thus, we've made a cyclone with air curving counterclockwise around low pressure.
    j. If the air parcel approaches isobars that are curving **clockwise**, inertia will carry it toward lower pressure.
        i) A component of the pressure gradient force is now pointing in the direction of parcel motion.
        ii) The parcel speeds up, increasing the Coriolis force, which makes the air bend to the right.
        iii) The air remains parallel to the isobars but moves quicker than it did when the motion was purely geostrophic.

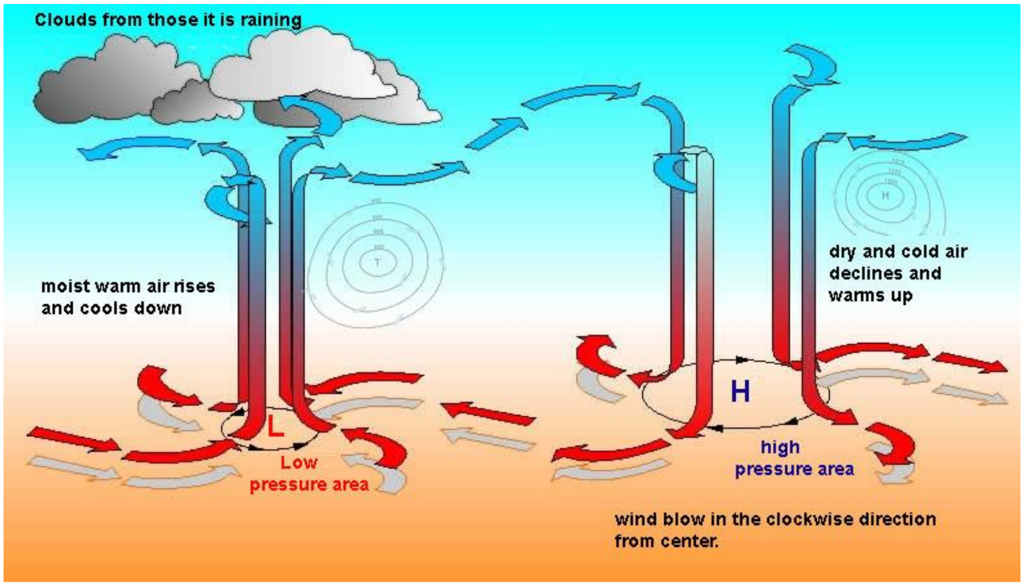
4. Let's combine our 4 fundamental forces.
    a. Pressure gradient force and Coriolis make straight-line geostrophic flow, low pressure to the left.
    b. Centripetal gives us curvature, counterclockwise around low, clockwise around high---still parallel to isobars.
    c. Friction gives us a little cross-isobar blow into low and our of high.



    d. Notice that owing to friction, wind can cross isobars away from high and toward low pressure.



e. In this situation, the air is converging into low pressure from below.
   i) Bringing air into low pressure at the surface creates upward vertical motion in the cyclone.
   ii) Rising air can become saturated and possibly unstable, resulting in clouds and storms.
   iii) Meanwhile, the surface divergence out of the high implies downward motion in the anticyclone, and we usually associate high with stable and clear conditions.



f. Additionally, we saw that isobar curvature affects wind speed so that, for the same isobar curvature, as the air curves counterclockwise, the wind is sub-geostrophic.
   i) The flow clockwise around highs is super-geostrophic.
   ii) This is an apparent paradox, because we often wee strong wind around lows, and we associate highs with weak winds.

g. In practice, isobar spacing around lows can be much smaller than around highs, and that's what leads to the faster winds.
   i) The reason we don't usually see tight pressure gradients around highs stems from the combination of the forces.
   ii) Pressure gradient and centrifugal force result in cyclostrophic balance.
   iii) Coriolis has no role here; this is local-scale rapid spin.
   iv) Spin creates low pressure, as we see when we create a vortex in a glass of water.

E. Summary:
   1) There are 4 fundamental forces that determine the horizontal wind.
   2) Pressure gradient force is directed form high to low pressure, and in the absence of other forces, nature moves mass from high to low pressure.
   3) The Coriolis force acts to the right following the motion in the Northern Hemisphere, to the left following the motion in the Southern Hemisphere, and is zero at the equator.

4) The Combination of these two forces, pressure gradient and Coriolis ----geostrophic balance.
5) Geostrophic balance represents straight line flow, parallel to isobars, blowing with low pressure to the left, at least in the Northern Hemisphere, and the speed of the geostrophic wind determined by isobar spacing.
    a. This balance applies to the large-scale wind, not the sea breeze, but rather to air flowing over long distances and blowing for days, weeks, and longer.
    b. But the geostrophic balance has already revealed to us why the equator to pole temperature difference doesn't result in a hemispheric se breeze, blowing alon the surface from pole to equator.
    c. Earth's rotation, through the Coriolis force, has spoiled this.
6) Friction acts near the ground to reduce wind speeds.
    a. We saw that friction disturbs the geostrophic balance of pressure gradient and Coriolis forces, which is the wind that is not blowing towards low pressure, as Nature desires.
    b. It does it by acting directly and specifically against the Coriolis force, thereby letting the wind find its way towards low pressure, at least a little bit.
7) With the fourth force, we saw that we could choose to interpret it as centripetal or centrifugal, or centripetal versus something else, depending on what we found to be convenient.
    a. But the centripetal or centrifugal forces appear wherever there is spin.
    b. Centripetal forces act inward and are always real.
    c. Pressure gradient force is it's usual disguise.
    d. Centrifugal forces act outward and is always a reactive force only.
8) Gradient wind balance was made when this 2-headed force joined forces with pressure gradient and Coriolis forces.
    a. That explained why the wind turns counterclockwise around large-scale cyclones, areas of low pressure, and clockwise around anticyclones, or large-scale highs.
9) Adding friction to the gradient wind balance helped us understand one big reason why we associate low pressure systems with bad weather.
10) Friction lets air converge into large-scale cyclones at the surface.
    a. This makes the air rise in the cyclone, push from below, and this air can diverge out of anticyclones, leading to descent, one reason why we associate highs with clear weather.
11) We saw that to make the large-scale wind deviate from the straight and narrow path and turn counterclockwise, we had to slow it down.
    a. And to make it turn clockwise, we had to speed it up.
12) Circular flow around highs is super-geostrophic, and around lows, it's sub-geostrophic.
    a. And yet we often see strong winds and tight gradients around lows, but almost never around highs.
    b. The answer came from cyclostrophic balance, which showed that spin makes low pressure.

F. Questions:

1) What determines wind speed in nature?

2) What determines wind direction in nature?

3) If I were to shoot a rocket from Layton, Utah to Cabo San Lucus, Mexico, which way would it veer due to the Coriolis effect? (Relative to us) Why?

4) Relative to the earth's north pole, does the rocket in question 3 curve or go straight? Why?

5) Estimate how fast we are moving in Layton, Utah relative to the North Pole? (Report it in Km/hr)
6) Estimate how fast the people in Cabo San Lucas, Mexico are moving relative to the North Pole? (Report it in Km/hr)
7) Since the rocket left Layton, Utah and is going to land in Cabo San Lucas, Mexico, how fast is it moving towards the west when it lands? (Report it in Km/hr)

8) If I shoot a rocket directly east from Layton, Utah, which direction would it veer?

9) Why does the Coriolis force act to the left following the motion in the Southern Hemisphere?

10) Why does the Coriolis force vanish at the equator?

11) If the Earth did not rotate on its axis, would we still have winds? If so, what would the average wind direction be in Layton, Utah.

12) It has been claimed that, in the Northern Hemisphere, the right-hand rails of railroad train tracks wear out faster than the left-hand rails. Why? (Presume that only one direction of motion is permitted on these tracks.)

13) Explain the formation of a geostrophic wind.

14) Unlike winds aloft, which blow nearly parallel to the isobars, surface winds generally cross the isobars. Explain what causes this difference.

15) What are the general weather conditions to be expected when the pressure tendency is rising? When the pressure tendency is falling?

16) For surface low pressure to exist for an extended period, what condition must exist aloft?

17) It is theoretically possible for large-scale wind to be able to blow clockwise around large-scale lows in the Northern Hemisphere. This is termed an antibaric low. For a given isobar spacing, would you expect winds around an antibaric low to be stronger or weaker than their couterparts around a normal low?

18) Prepare a diagram (isobars and wind arrows) showing the winds associated with surface cyclones and anticyclones in both the Northern and Southern Hemispheres.