GLG120 Weather and Environment **Name: ___________________**
Lab/Homework: Pressure and wind patterns

Part 1: Wind velocity resulting from pressure gradients and force balances

Background information on pressure gradients, force balances and wind

Wind velocity – i.e., both its direction and speed – results from a balance of forces in the atmosphere. In mathematics, velocities and forces are examples of what we call **vector** quantities: they have both a magnitude (speed in the case of wind) and a direction. When we combine (add) vectors, we must consider both the magnitudes and the directions of all the vectors in the combination (sum). When we say that forces are balanced, it means that all the forces added together must equal zero, yielding no net force in any direction: in other words, some force(s) must cancel out other(s).

When we represent the force balance with a diagram, arrows indicate the forces and the resulting wind. Each arrow's direction shows the spatial orientation of the corresponding vector, while the arrow's length describes that vector's relative magnitude. (Note: Arrow diagrams can also illustrate situations where forces are not in balance, i.e., where there is a net force in one direction or another. We will discuss some examples in lecture, but you need not draw diagrams for such scenarios.) We will quickly outline the three forces contributing to the force balance that determines wind velocity; then you will draw examples of force balances for different scenarios.

Only one force, the pressure gradient force, causes wind to occur, but one or two others modify the wind's velocity. Let's consider directions and magnitudes of each.

- **pressure gradient force** (PGF): the force that actually generates wind!
  - direction: The pressure gradient always points from high (H) to low (L) pressure, perpendicular (90^o) to pressure contours, thus so does the PGF.
  - magnitude: The stronger the pressure gradient, the higher the PGF, and a higher PGF generates a faster wind. The more closely contours (e.g., isobars) are spaced, the stronger the gradient. Always measure contour spacing, like pressure gradient (and PGF) itself, perpendicular to contours.
- **Coriolis force**: the "force" (strictly speaking, "effect") that arises from the Earth's rotation and bends the paths of objects moving freely above the Earth's surface (baseballs, rockets, currents, etc.)
  - direction: The Coriolis force is always perpendicular to the actual travel direction of the moving mass (e.g., the wind = moving air). In the northern hemisphere, the arrow for the Coriolis force points 90^o to the right of the arrow for wind direction; in the southern hemisphere, 90^o to the left.
  - magnitude: The Coriolis force increases with wind speed and latitude: in other words, as winds become faster and/or are further from the equator.
- **friction**: the "braking" force caused by surface interactions
  - direction: Friction always points in the opposite direction of the motion ("backwards") – i.e., 180^o from the direction of the wind itself.
  - magnitude: Friction increases with wind speed and also with surface roughness. It is only significant when wind is at or near Earth's surface, so for winds aloft, we omit it from the force balance.

When you draw force-balance diagrams for the following scenarios, always start by identifying the pressure gradient and drawing the PGF arrow, pointing from high to low pressure. Then balance the PGF: either with the Coriolis force alone or with combined effects of the Coriolis force and friction (at right angles to each other, due to their respective relationships to wind direction). Arrow(s) for the force(s) balancing the PGF must point "away from" the PGF. Lastly, add an arrow for the resulting wind direction, based on its geometric relationship to the Coriolis force and, if applicable, to friction.

1) Relative magnitudes of the forces
   In drawing your force-balance diagrams (questions 2 – 4), do not worry about the relative magnitudes of the forces (lengths of the arrows): just focus on identifying the correct directions. Instead, let's consider magnitudes briefly here.
   a) If the PGF increases, does the Coriolis force increase, decrease, or remain the same? Explain.

   b) If the PGF increases, does friction increase, decrease, or remain the same? Explain.

2) Force balances and winds aloft
   Strictly speaking, contours describing pressure on upper air maps are not isobars: instead, they represent the altitude above sea level of a continuous surface aloft where the air pressure has a given value. The maps on the next page describe the 500-mb surface, where ~½ the atmosphere is above and ~½ below. Height units are meters, so the surface is >5½ km (>3⅓ miles) above sea level. Since higher altitude of the surface corresponds to higher pressure aloft, however, you can interpret the pressure gradient from height contours just as you would from isobars.
   a) Identify the forces involved in determining wind velocity aloft. How many arrows will each of your force-balance diagrams for winds aloft include? What are they?

   b) Northwest Canada example (top of next page): Identify the pressure gradient and draw your force balance. (We will do this together in class: follow my lead.)

   c) What is the general wind direction aloft in the northern hemisphere? Note: Winds are named for the direction they blow from: i.e., a sea breeze blows inland from the sea, and a south (or southerly) wind blows from the south to the north.

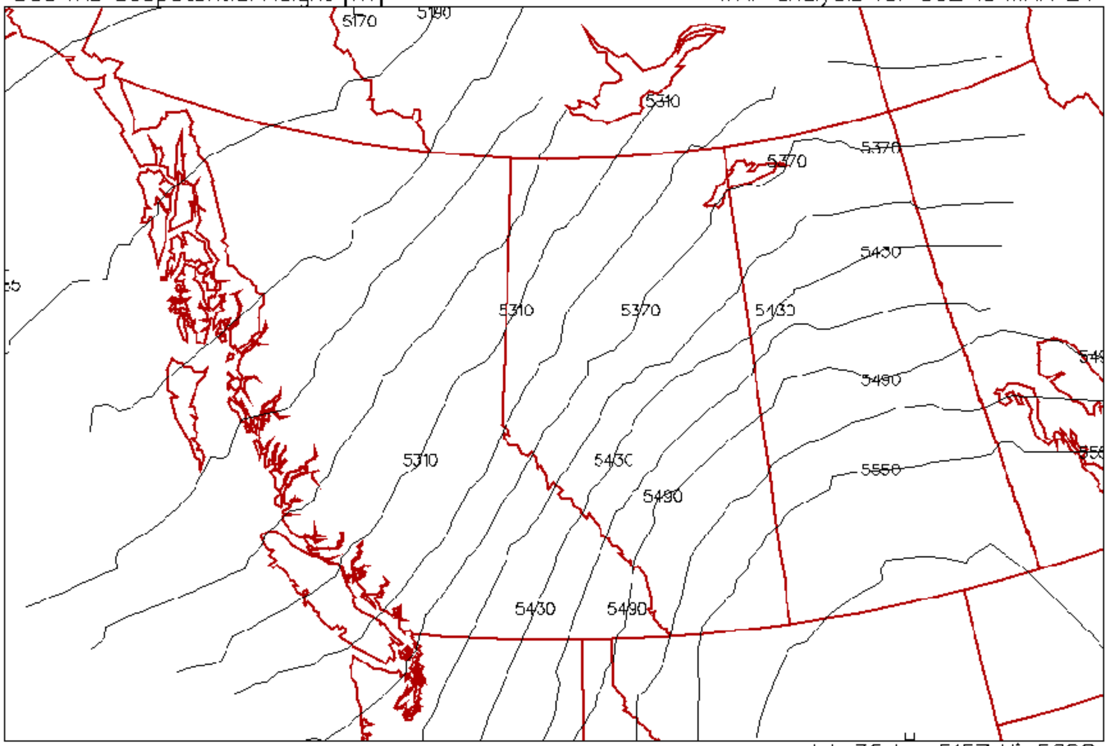
   d) South Africa example (bottom of next page): Identify the pressure gradient and draw your force balance. (Do this on your own; ask for help if needed.)

   e) What is the general wind direction aloft in the southern hemisphere?

   f) What is the geometric relationship (parallel/perpendicular/crossing at an angle) between wind direction and contours (height of the pressure surface) aloft?

Plymouth State Weather Center

500 mb Geopotential Height [m] WXP analysis for 00Z 10 MAR 24



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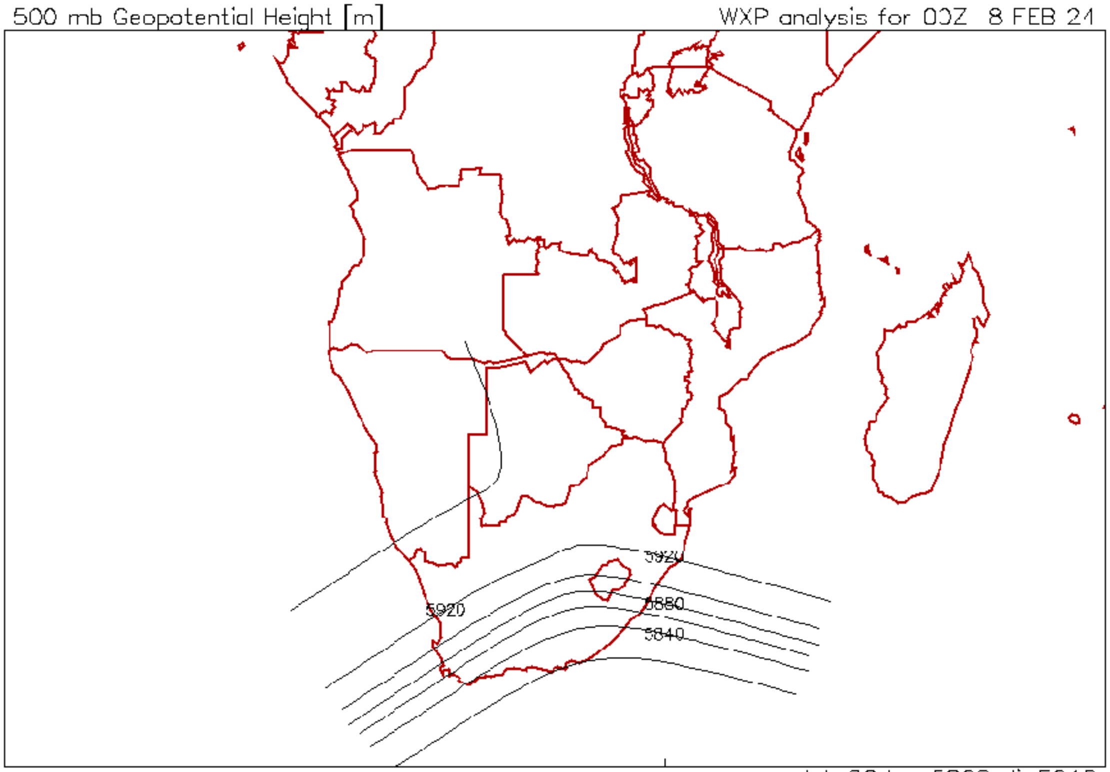
Plymouth State Weather Center

500 mb Geopotential Height [m] WXP analysis for 00Z 8 FEB 24



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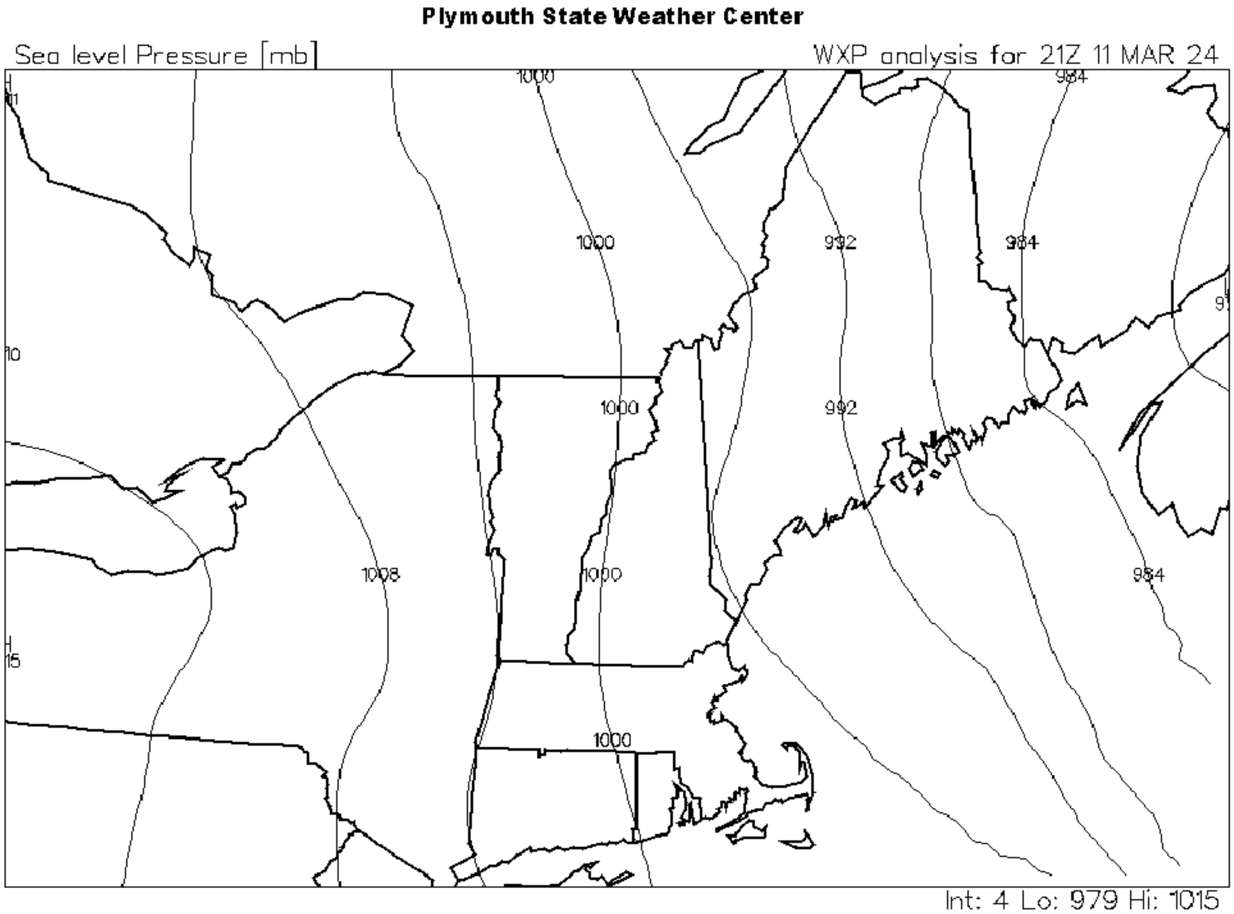
3) <u>Force balances and winds at Earth's surface</u>
   a) Identify the forces involved in determining wind velocity at Earth's surface. How many arrows will each of your force-balance diagrams include? What are they?

   b) New England example (below): As always, start by identifying the pressure gradient, then draw your force balance. (We will do this together as a class.)



   c) Australia example (next page – look at center of the continent where the contour pattern is simplest): Identify the pressure gradient and draw your force balance.

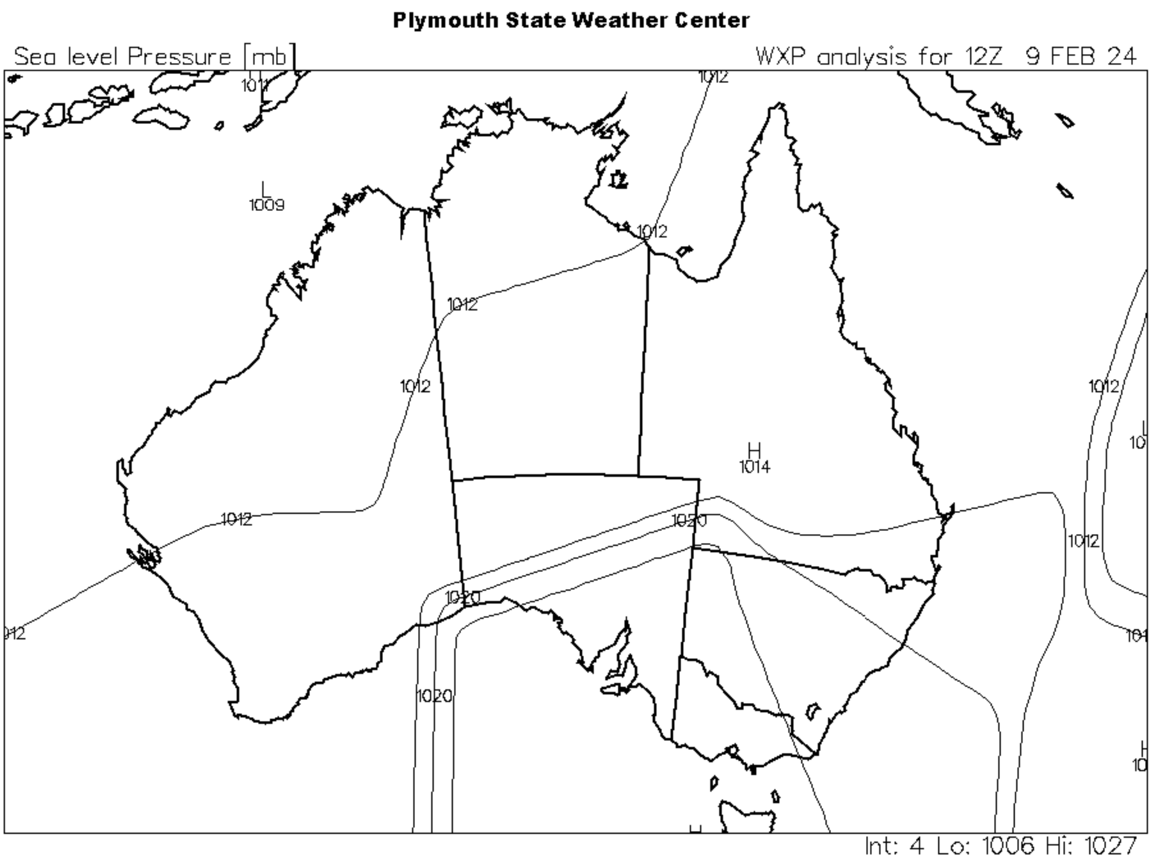
   d) What is the geometric relationship (parallel/perpendicular/crossing at an angle) between wind direction and contours (isobars) at Earth's surface?

4) <u>Compare and contrast force balances for winds aloft and winds at the surface.</u>
   a) What do all your diagrams have in common?

   b) How does the force balance differ at the surface from aloft?

c) How does the relationship of the wind direction to the other forces/arrows differ?

wind direction relationship to:	aloft	at the surface
pressure contours/isobars		
PGF		
Coriolis force		
friction		



Optional practice/preparation for question 5:

a) Add force balance diagrams in other locations on the preceding maps. Remember that pressure gradient – and the PGF – are perpendicular to pressure contours/isobars, so your force balance diagrams (and resulting wind directions) will not be parallel everywhere on the map unless the contours are parallel too.

b) Add wind arrows in other locations on the preceding maps. Instead of drawing the force balance diagram, analyze it mentally and draw the resulting wind arrow.
- How many and which forces are involved? (How do you know?)
- Will the resulting wind arrow cross contours or not? (How do you know?)
- Which direction does the Coriolis force point, relative to the wind direction? (How do you know?)
- Which way will the wind arrow point?

Background information: Pressure contour patterns, ridges and troughs

Notice that pressure contours often extend roughly east-west, especially aloft, but may also meander or "zigzag," especially if the map area is sufficiently large. In other words, as you follow the contour lines from the west to the east across the map, the lines may trend northeast-southwest, then northwest-southeast, then northeast-southwest again. Since contour lines cannot intersect (remember why!), the nearby pressure contours in the map area display the same general pattern.

Meteorologists describe a meandering contour pattern like this as consisting of alternating ridges and troughs.

- A **ridge** is an elongated region of high pressure extending towards high latitude.
- A **trough** is an elongated region of low pressure extending towards low latitude.
- The **axis** of a ridge or trough is a line dividing the ridge or trough into two roughly equal halves, that are roughly mirror images of each other. The axis connects the locations where each pressure contour in the pattern "rounds the corner" of the meander. In other words, on one side of the axis the contours trend northeast-southwest, on the other side the contours trend northwest-southeast, and on the axis itself the contours trend east-west. Axes (plural of axis) will trend roughly north-south, but not necessarily due north-south.

In the northern hemisphere, ridges extend northward while troughs extend southward (U or V shape on the map). Of course, the corresponding compass directions are opposite in the southern hemisphere.

On the next page, you will be asked to identify and label ridges and troughs based on the pattern of pressure contours. Now that you know what they are, you need to know how to label them.

- By convention, <u>ridge axes are marked by serrated lines</u>. Serrations are small zigzags: if the axis itself trends due north-south, then the zigzag sections trend (alternating) northwest-southeast and northeast-southwest.
- By convention, <u>trough axes are marked by dashed lines</u>.

A common mistake is to add serrations or dashes not to the axis line itself, but instead to or near the pressure contours in its vicinity. You might start by identifying the trend of each axis in pencil using a plain solid line, then decide whether that axis represents the center of a ridge or of a trough, and lastly modify your pencil line (or redraw a new one in the same place) to incorporate the correct symbols (serrations or dashes).

While we are dealing with directions and definitions, here are a few more terms you will encounter related to wind directions, especially aloft.

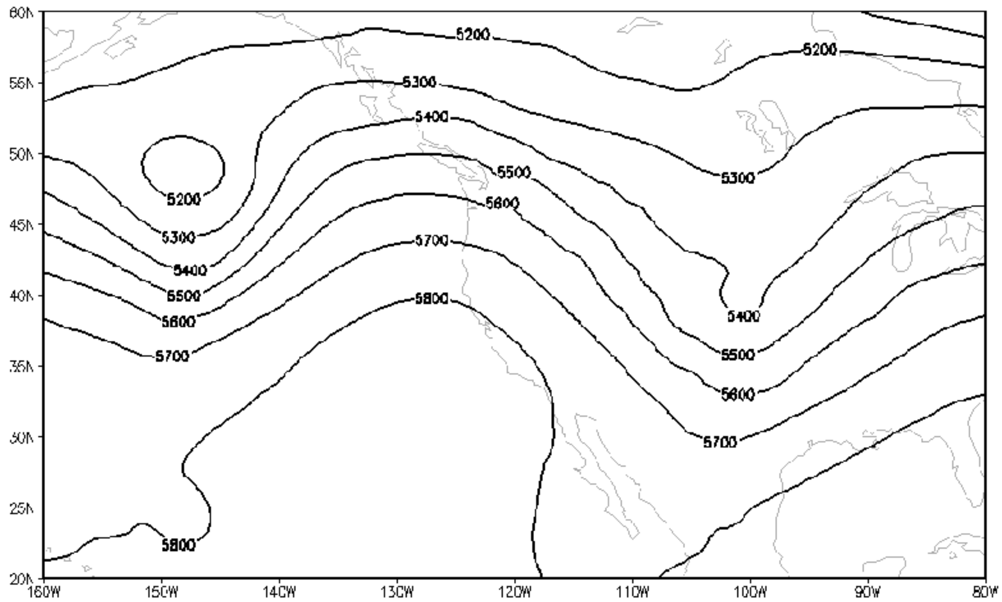
- The east-west component of wind motion is called **zonal** flow.
- The north-south component of wind motion is called **meridional** flow. (A good way to remember the difference: lines of longitude, running north-south on the globe, are called meridians, so meridional flow is parallel to the meridians.)
- **Flat** flow describes situations when the meridional component is very small.

Over time, flow aloft alternates between flatter (mostly zonal) and more meandering (with a strong meridional component). In question (2), you identified how wind directions aloft relate to the directions of the pressure contours. Based on that work, it should make sense that when the pressure contours aloft show a prominent pattern of ridges and troughs, meridional flow is significant.

5) <u>From pressure surface height contours or isobars directly to wind direction</u>

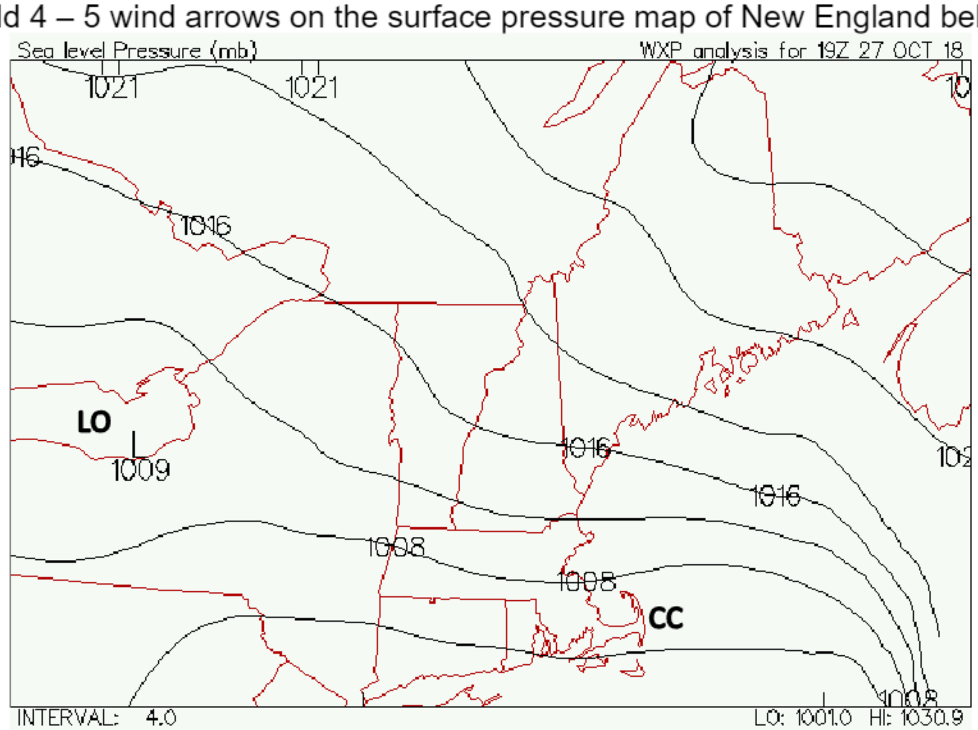
On each map below, add arrows showing wind directions. Analyze force balance mentally, but DON'T draw force-balance diagrams: instead, generalizing what you have learned, use the contour pattern to guide you in drawing your wind arrows.

a) Add 4 – 5 wind arrows to the 500-mb map for North America below.



b) Mark its ridge axes with serrated lines and trough axes with dashed lines.

c) Add 4 – 5 wind arrows on the surface pressure map of New England below.



d) Is the wind faster over Cape Cod (CC) or Lake Ontario (LO)? How can you tell?

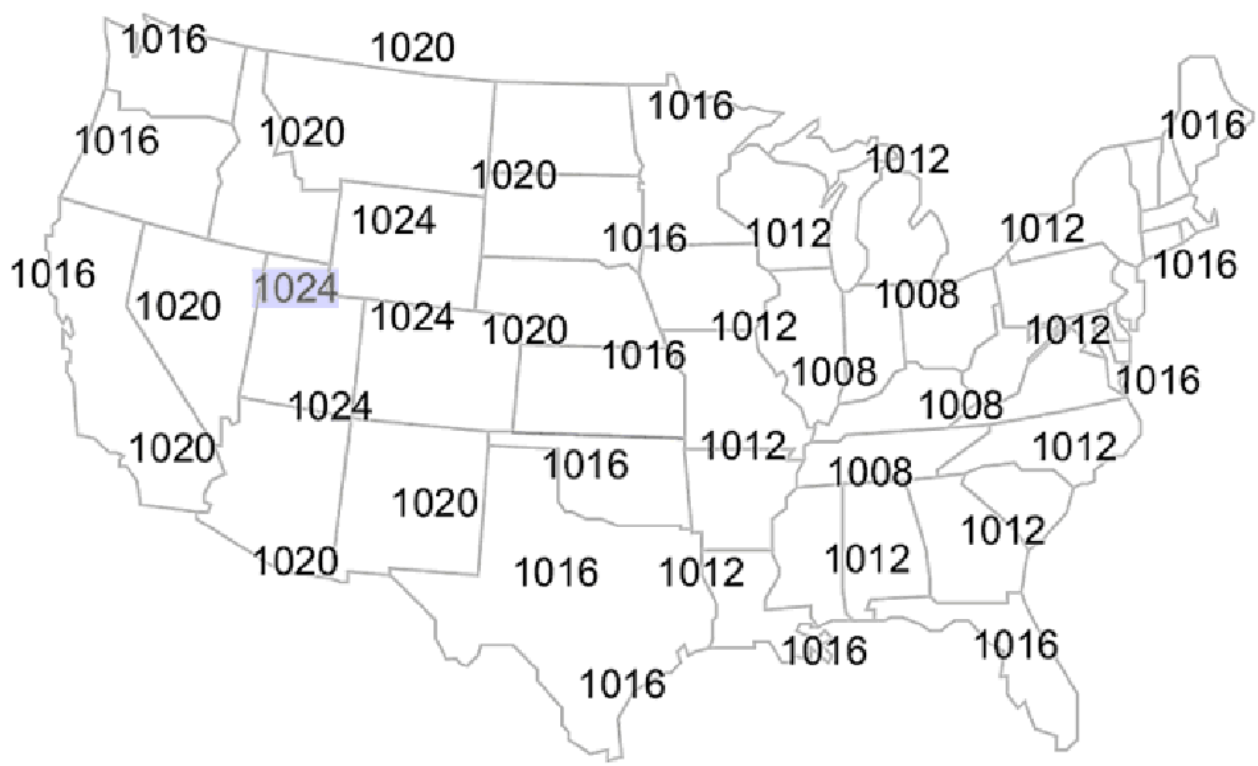
Part 2: Cyclonic and anticyclonic circulation

Background information: Pressure centers and circulation

The term **pressure center** refers to locations of high or low pressure, where pressure contours (near Earth's surface: isobars; aloft: elevation contours of a given pressure surface) in the map region wrap around, often making closed circles, in a bullseye-like pattern. On English-language weather maps, centers of high pressure are labeled with a letter H, often in blue, and centers of low pressure with L, often in red. The letter goes at the center of the innermost ring/loop in the bullseye contour pattern.

You have seen in Part 1 that you can use the pressure gradient, described by the contour pattern, to analyze the resulting wind direction. When you apply this same approach around a pressure center, drawing 4 or more wind arrows around it, you will discover that together the arrows create a spiraling pattern. The spiraling movement of air around a pressure system is called **circulation**. The term **cyclonic** describes the wind pattern around centers of low pressure (L's), while the term **anticyclonic** describes the motion around centers of high pressure (H's).

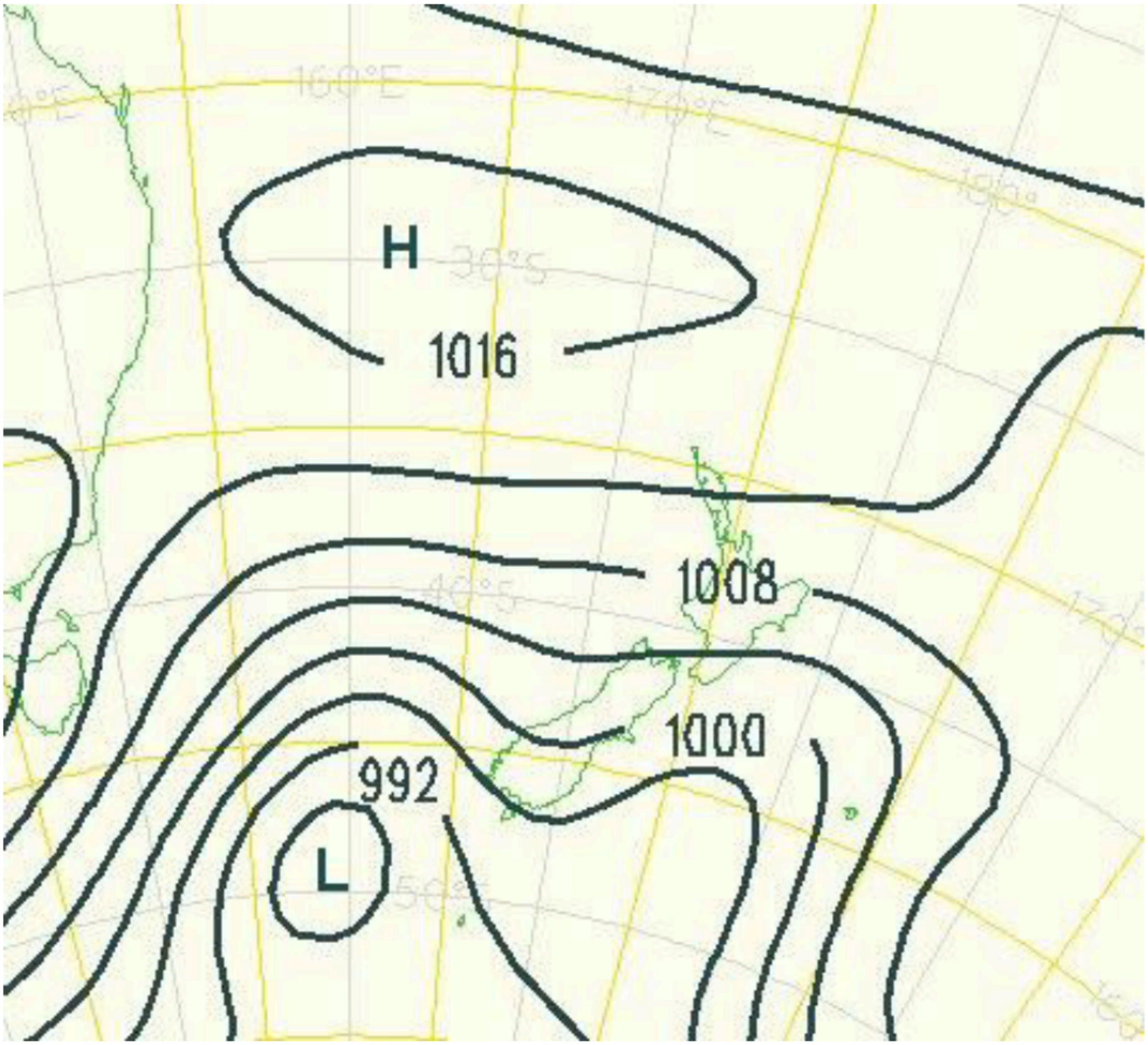
1) <u>Analyzing surface pressure by drawing isobars and labeling pressure centers</u>
   a) The map of the U.S. below shows values for surface pressure. Treating the center of each labeled value as a data "point," draw isobars, using a contour interval of 4 mb. (To warm up, this is an easy example map where you can just "connect the dots." We will look at station models and real data later.)



   b) Your isobar pattern should reveal a center of high pressure and another of low pressure. Label these pressure centers H and L, respectively.

2) Describing wind directions and circulation around pressure centers
Next you will add wind arrows to the U.S. map on the previous page that you just contoured. To guide your thinking (so, before you draw anything), consider and answer questions (a) and (b) below.
   a) Think about the how the pressure gradient force generates wind. In the following sentences, fill in the blanks, either with “outward from” or “inward towards.”
      - Winds blow __________________ areas of high pressure.
      - Winds blow __________________ areas of low pressure.
   b) Think about how wind paths curve due to the Coriolis force. In the following sentences, fill in the blanks, either with “right” or “left.”
      - The Coriolis force (arrow) points to the ______ of the wind direction (arrow) in the northern hemisphere, and winds in the northern hemisphere curve to the _______.
      - The Coriolis force points to the _______ of wind direction in the southern hemisphere, and winds in the southern hemisphere curve to the ______.
   c) Based on your analysis, now add wind arrows around the two pressure centers. (We will complete this example together in class: follow my lead). Draw at least four wind arrows around each pressure center (north, south, east and west).
   d) Deflection of wind directions by the Coriolis effect causes circulation – i.e., a spiraling pattern – of the winds around any pressure center. For each of the following pressure centers, describe the circulation using two words: either “clockwise” or “counterclockwise” (with respect to the center of circulation) and either “inward” or “outward” (towards or away from the pressure center).
      - H in the northern hemisphere?
      - L in the northern hemisphere?
      - H in the southern hemisphere?
      - L in the southern hemisphere?

3) An example from the southern hemisphere
   a) Add wind arrows around the pressure centers shown on the map of New Zealand on the next page. Draw at least four arrows around each pressure center.
   b) In what ways (if any) is this circulation pattern the same as wind circulation around pressure centers in the northern hemisphere?
   c) In what ways (if any) is this circulation pattern different from wind circulation around pressure centers in the northern hemisphere?



Hints/reminders before you start drawing arrows:

1) Do the contours on this map describe pressure at the surface (isobars) or aloft (height contours of a pressure surface)? How do you know?
2) Based on your answer to (1), which forces are involved in determining the wind direction, at any location on the map?
3) Based on your answers to (1) and (2), what should be the geometric relationship (parallel/perpendicular/crossing at an angle) between your wind direction arrows and the contours? Review your answers in Part 1 to questions (2f) and (3d).
4) Because this map shows pressure centers – i.e., centers of circulation – you should expect wind direction to be different to the north, south, east and west of each pressure center, rather than relatively consistent across the map area (as in Part 1). Make sure your arrows illustrate the spiraling nature of circulation.
5) Recommendation: Avoid drawing strongly curving arrows. It is easy to get the direction of curvature wrong (backwards), implying a mistaken understanding of the force balance, even if the general direction of travel is correct.

Part 3: Wind power

1) Importance of wind speed
Wind power increases with the cube of wind speed: $P \propto v^3$ (where the symbol $\propto$ stands for "is proportional to"). When harnessed by machines (such as sails or turbines) that power can accomplish work or generate electricity. An electrical turbine converts the mechanical energy of its moving blades to electricity, moved by the wind, to electricity by spinning a large magnet, which generates an electric current: a great example of the principle of conservation of energy in action! Powerful winds are also responsible for significant damage during storm events, including hurricanes, tornadoes, derechos and blizzards.

   a) Fill out the chart to the right with values for Y to complete the sentence: "As wind speed increases X times, power (and electricity output) increases Y times."

X	Y
2	
3	
5	
10	

   b) Utility-scale wind power installations require average wind speeds of ~6 m/s (13 mph). How many times more power is produced by a 13-mph wind than by a 6.5-mph wind? Show your work.

   c) How many times more power is produced by a 20-mph wind than by a 5-mph wind? Show your work.

   d) When a tropical storm's sustained wind speeds reach 74 mph, it becomes classified as a Category 1 hurricane (in the Atlantic Ocean) or typhoon (in the Pacific and Indian Oceans). A Category 5 storm has sustained winds >155 mph. (See Appendix F in your textbook for more on the Saffir-Simpson Hurricane Scale.) Approximately how many times more (destructive) power do the winds in a Category 5 storm have, compared to winds in a Category 1 storm? Show your work.

2) Forces affecting wind speed
   a) Commercial wind turbines stand ~260 m (80 ft) above the land (or water) surface. Why are wind turbines so tall? (Watch this short video from the U.S. Department of Energy to confirm your answer.)

b) Think about what you know about the geography of the U.S. and its wind patterns. Where in the U.S. do you predict that the highest wind speeds are encountered? Why? (After thinking on your own, you may find it interesting to compare your answer to the maps of wind speed and potential for electricity generation at the U.S. Department of Energy's WINDExchange website.)

c) Compare the locations with high wind power potential to the parts of the country with the highest population and electricity demand. Do they match? What effect might this have on the economic viability of wind power?

3) Wind direction and wind power
Most turbines are designed to face into the wind (and to rotate as the wind direction changes to maintain this orientation). Based on what you know about wind patterns, in what compass direction do most turbines in North America face?

4) The past, present and future of wind power for electricity generation
Wind power in the U.S. has grown from 0.1% of electricity generation in 1990 to 8.4% in 2020 (source: U.S. Energy Information Administration), with federal initiatives aiming to expand this share to 20% by the year 2030. (China leads the world in wind electricity production, with the U.S. at #2.) As wind power technology matures, interest has turned to offshore wind farms. As of 2016, ~⅔ of global offshore wind power was generated in Northern Europe, principally for the U.K. and Germany, but China is also investing in this technology. The first U.S. offshore wind farm (a 30-MW installation off the coast of Rhode Island) began operating in December 2016 and others have been proposed but are still in the permitting stage.

a) What is the main advantage of offshore wind farms over land-based turbines in terms of power generation? In other words, why are conditions more favorable for power generation over water than land?

b) What are some of the logistical challenges to installing wind farms offshore?

Part 4: Depicting surface pressure and pressure tendency in the station model

Background information: Station model notations for pressure and its tendency

Surface air pressure on weather maps is always corrected to a sea-level equivalent, expressed in mb, and depicted in the station model to the upper right of the station circle. To save space while preserving precision, meteorologists abbreviate pressure values using a three-digit code: the last digit represents a decimal place, but the decimal point is omitted, while the two digits preceding it represent the tens and ones places. Recall that average sea-level air pressure is 1013.25 mb, and typical values fall within the range of 980 to 1040 mb. Since they are very rarely more than 50 mb above or below 1000 mb, it is possible to omit the leading 10 in values over 1000 and the leading 9 in values below 1000: anyone analyzing the map can mentally supply the missing digit(s) by making the choice that yields an answer closer to 1000. On occasions where values fall outside this normal range, the overall pattern or trend on the map supplies enough additional context to recognize the leading digit(s).

The station model also may indicate **pressure tendency**, the change in surface air pressure over the past three hours. This information is encoded immediately to the right of the station circle, just below the pressure value, and includes a numerical value followed by a symbol. The numerical value indicates the extent of change; again, while no decimal point is included, the last digit always represents the decimal place. Usually, two digits are sufficient to describe the change. The symbol is a line pattern, analogous to a trend line on a graph, describing whether pressure has risen or fallen, and whether the trend has been continuous or shown any changes. Examples of these line patterns are included in Appendix B of your textbook, along with other station model details.

(For your information: Upper air maps, constructed based on data collected by radiosondes sent aloft by weather balloons, also display data using station model notation, but with slightly different conventions. The number to the upper right still describes pressure but does so by giving the altitude of the pressure surface, usually in decameters, i.e., 10s of meters, above sea level. Correspondingly, pressure tendency, displayed just below the pressure surface altitude, is described as the height tendency of that pressure surface, over the past twelve hours. To the lower left, where the surface station model shows dew-point temperature, the upper air station model often describes humidity by displaying the dew-point depression, which is the difference between air temperature and dew-point temperature. You are not expected to know these details.)

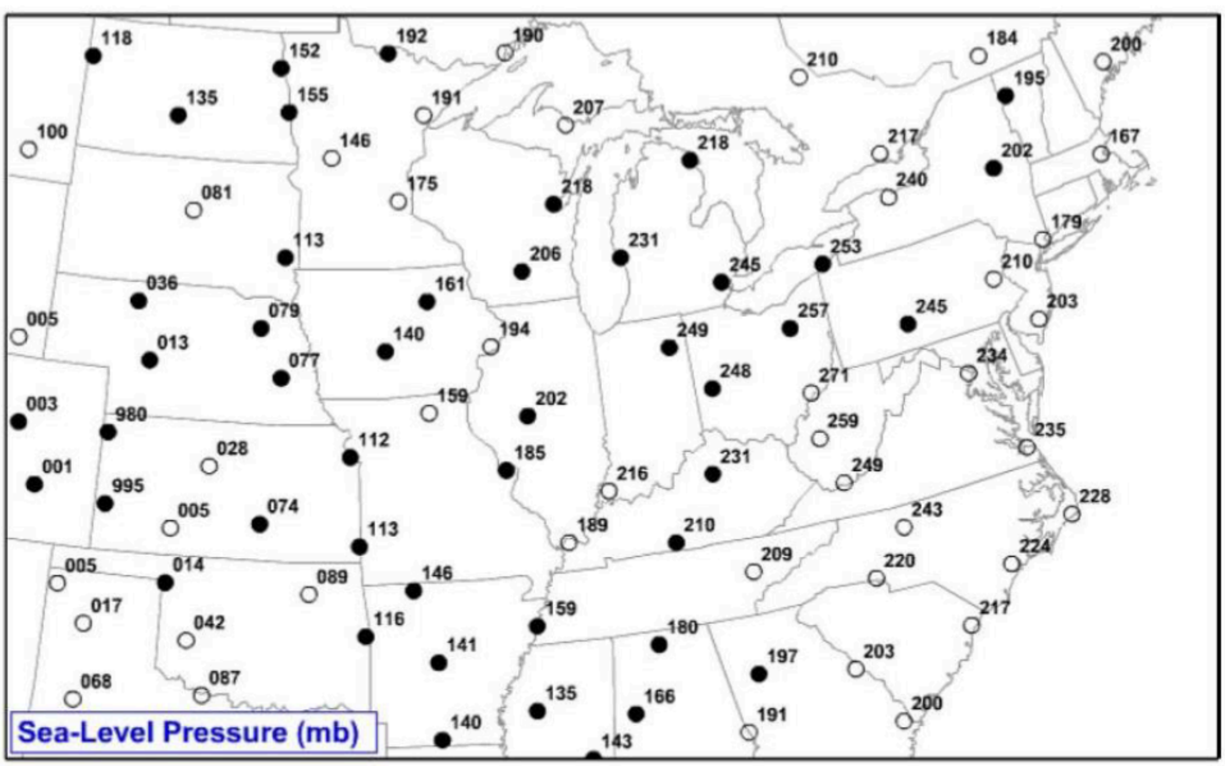
1) Converting air pressure data to station model notation
   Practice converting each of these (sea-level-equivalent) air pressure readings (in mb) to the station model notation used on weather maps.
   a) 1013.4
   b) 997.8
   c) 982.3
   d) 1024.7
   e) 991.6
   f) 1000.5

2) Decoding station model notation for air pressure
   Now practice decoding these values, expressed using the station model convention, to give the actual sea-level-equivalent air pressure.
   a) 872
   b) 014
   c) 129
   d) 938
   f) 301
   g) 960

3) Decoding station model notation for pressure tendency
For these example station models, describe the pressure tendency (rising/falling, continuous change or not, etc.) and calculate the actual air pressure three hours earlier. Calculation hints: If the pressure tendency is falling, then was the air pressure three hours ago higher or lower? Based on that answer, should you add or subtract to find the pressure value at the earlier time?

a) b) c) d)

4) Contouring practice and review of circulation
   a) Review the rules of contouring from your isotherm homework (e.g., contour lines must never cross, maintain a consistent contour interval, etc.)
   b) Add isobars to this surface weather map using a 4-mb contour interval.
   c) Label each isobar with its value in mb. Tips: Start with the 1000-mb isobar. Add labels as you work. Remember to “translate” from the three-digit code to mb.
   d) Label any pressure centers (H and/or L) revealed by the contour pattern.
   e) Add at least 10 arrows describing wind directions, enough to illustrate circulation around any pressure centers (review Part 2) and to demonstrate your understanding of the force balance (review Part 1).



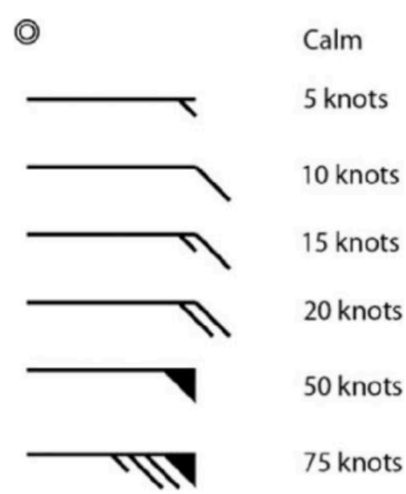
Part 5: Depicting winds in the station model

Background: Describing wind speed, mapping wind speed and direction

Weather stations report wind speed using units that are probably unfamiliar to you: **knots** (sometimes abbreviated kn or kt), which are nautical miles per hour. One **nautical mile** is (now officially defined as) 1,852 meters or ≈1.15078 statute miles (the miles you are familiar with). Accordingly, 1 knot is 1.852 km/hr or ≈1.15 mph. Where do knots and nautical miles come from? Historically, a nautical mile was defined as 1 minute of latitude (also 1 minute of longitude at the equator), where 1 minute is 1/60 of a degree of latitude (or longitude). Thus, a ship traveling at 60 knots along a meridian (or along the equator) would cover 1 degree in an hour. The word "knot" comes from a device that sailors used to measure their ship's speed: a rope with knots at equally spaced, calibrated intervals, attached to a weighted buoy that remained stationary on the water surface as the ship advanced. After throwing the weighted buoy overboard, one sailor kept track of time with an hourglass, while another allowed the rope to play out behind the moving vessel, counting how many knots slipped through the fingers.

Historically, the greatest demand for wind data came from sailors, and today aviators have similar needs. Navigation charts covering large distances on the (nearly) spherical Earth typically use a latitude-longitude grid, which makes the nautical mile a convenient distance unit. It then becomes useful to describe travel speed of one's vessel, and of winds or currents that may affect it, in knots. Both to serve the shipping and aviation industries and for ease of comparison with historical data, weather stations continue to record wind speed in knots, and weather maps used by meteorologists still display it this way. Maps reporting wind data to the "landlubber" public typically convert speeds into units in common local use: mph in the U.S. and km/hr almost everywhere else. The simplest way to "translate," if you do not need to be exact, is to remember that the wind speed in mph is slightly less than the value shown in knots.

The station model indicates wind direction with a line, called the **staff**, extending from the station model circle towards the direction from which the wind is blowing. The exception is for calm conditions: lack of wind (direction or speed) is recorded as a slightly larger circle surrounding the station circle. If you imagine yourself standing in the station circle looking down the staff, the wind would be blowing in your face. Alternatively, you can mentally add an arrowhead to the end of the staff that meets the station circle to picture the wind blowing towards the station. The wind direction staff is the only component of the station model that – by necessity – does not have a fixed location around the station circle.



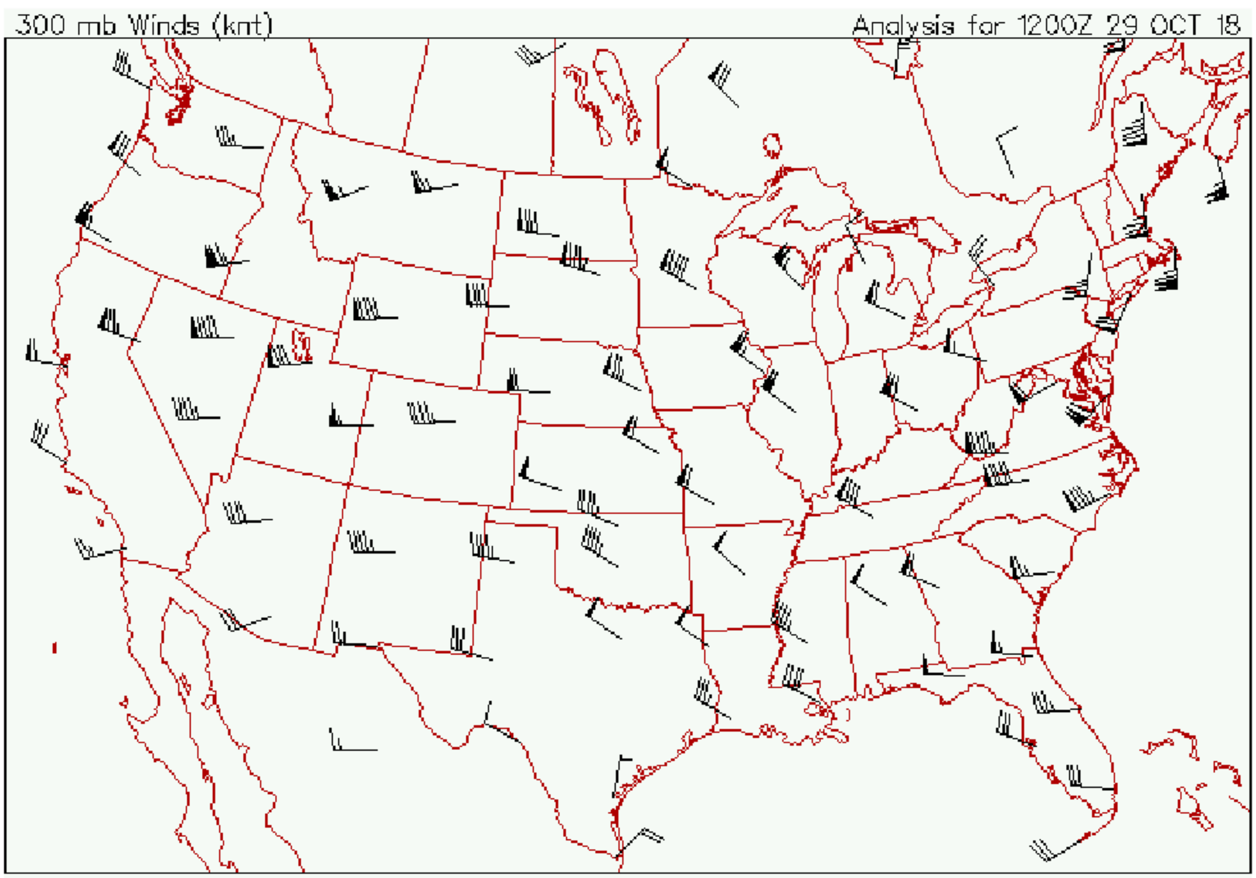
The chart to the right indicates how wind speed is represented in the station model using **barbs** or **flags** on the staff. A short or "half" barb indicates a speed of 5 knots, a long or "full" barb 10 knots, a flag 50 knots. To indicate other speeds, multiple barbs or flags are "flown" from the staff in combination, as shown by the 75-knot example at the bottom. (The notation may remind you a bit of Roman numerals, where LXVII = 50 + 10 + 5 + 1 + 1 = 67.) The barbs or flags are always drawn extending to the right of the staff and angled slightly upward, and in combinations the symbols indicating larger values are closer to the top of the staff. Notice the precision implied by the symbolic scale: values that are not even multiples of 5 must be rounded to the nearest multiple. Thus, the same short barb used for 5 knots could also represent a wind blowing at 3 or 7 knots. Some sources acknowledge this practice by listing a range of speeds associated with each symbol, but such descriptions tend to obscure the method of adding symbols in combination. An easy way to think about it is that each symbol or combination of symbols has a precision of +/-2.5 knots.

1) <u>Interpreting wind speed and direction from station model notation</u>
   The upper air map below describes conditions on the 300-mb pressure surface. Interpret the wind speed and direction aloft at the following locations:
   a) San Francisco, California

   b) northern Maine

   c) southernmost Texas

   d) Niagara Falls, NY



2) Inferring pressure contour patterns from wind directions
Pressure contours (in this case, altitude contours for the 300-mb pressure surface) are not plotted on this map, but you can make some inferences about the contour pattern based on the wind symbols and what you know about the relationship between wind directions and contours aloft. (Review Part 1.)
   a) In what compass direction do the contours describing the altitude of the pressure surface trend in Montana/Idaho/Wyoming? (e.g., N-S, E-W, NW-SE, etc.)

   b) In what compass direction do the contours trend in Arkansas/Missouri/Illinois?

   c) Are the contours more closely spaced in Arizona/New Mexico or in Illinois/ Wisconsin? Explain.

   d) Does an upper-level ridge or an upper-level trough run through New York state?

3) Contouring practice and jet streaks
   a) Using a colored pencil, identify stations with wind speeds at or above 100 knots. Using these stations as a guide, interpolate between the stations you identified to shade in one or more map region(s) where the wind speed is ≥100 knots.

   b) Using another color, shade in region(s) with wind speeds ≥50 and <100 knots.

   c) The boundaries between the areas you have identified – with wind speed ranges of 0-49 knots, 50-99 knots and ≥100 knots – represent contour lines of equal wind speed, called **isotachs**. In other words, your coloring has revealed isotachs defined with a 50-knot contour interval. Make sure that each boundary – i.e., each isotach – shows up as a clear line on your map.

   d) High wind speeds aloft do not occur randomly: you should notice a band that generally trends east-west but meanders somewhat (zigzags north-south) as well. Such bands, called **jet streams**, occur at latitudes determined by global wind circulation patterns. Jet streams are not fully continuous around the globe, consisting instead of several regions of accelerated air flow. The fastest regions in the center ("core") of the jet stream are called **jet streaks**. Use a labeled arrow to identify a jet streak on this map.

Part 6: Global wind patterns and convection

Background information: Convection and heat transfer

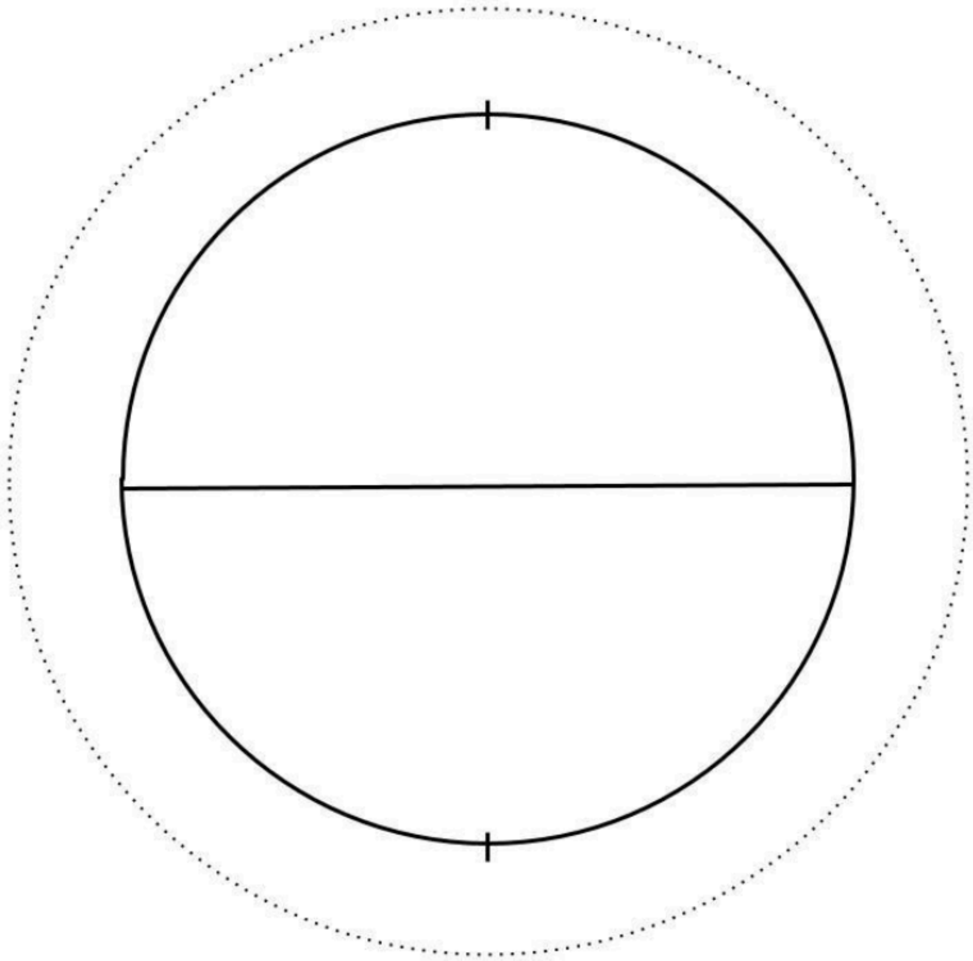
Recall that **convection** is a mechanism of heat transfer important in fluids (liquids and gases) heated from below: heated fluid becomes less dense (more buoyant) and rises above the heat source, initiating a flow where cooler fluid continuously moves toward the heat source to take its place, warms, and rises in turn. This continuous path of vertical and horizontal movement forms a loop called a **convection cell**. Convective motion of air is extremely important in understanding the atmosphere's behavior: we initially discussed atmospheric convection in terms of generating thermals, a local phenomenon, but convection also occurs over much larger spatial scales, right up to understanding global wind circulation. Between zones of vertical air motion (where air rises or sinks), the horizontal flow of air, sometimes called **advection**, is what we experience and describe as wind.

Because we have also emphasized that winds are generated by pressure differences, it is important to consider explicitly how the uneven heating of the Earth's surface – i.e., temperature gradients – leads to the formation of pressure gradients. Where the Earth's surface is heated, the air above also warms and rises. This movement of air away (upward) from the surface reduces surface air pressure. Where surface air pressure is low, air moves in to take its place: winds converge towards those low-pressure locations from areas with higher surface pressure. The pressure pattern aloft is opposite to that at the surface: where warm air rises, the upward transfer of air causes air pressure to be higher aloft than in neighboring locations, so the pressure gradient aloft points in the opposite direction of the surface pressure gradient.

1) Necessary conditions for convection
   How does the effectiveness of convection as a mechanism of heat transfer change in outer space? Explain your reasoning. (You may enjoy this short article from Scientific American describing early flame experiments conducted by NASA, which showed that in space a candle's flame is spherical and extinguishes itself.)

2) Persistent convective patterns
   If heat spontaneously flows from warm to cold regions and winds blow from regions of high pressure to low pressure, then why do imbalances or gradients of temperature and pressure persist? In other words, why don't atmospheric conditions "even out" around the globe?

3) The Hadley model: identifying fundamental temperature and pressure gradients
   George Hadley proposed a simple model as a starting place for understanding global atmospheric convection. To simplify, we pretend that the Earth is not rotating, so we do not need to consider how the Coriolis effect alters the wind's direction. Thus, the wind direction would be the same as the PGF: from high to low pressure. (We may also ignore friction for this analysis: in the absence of the Coriolis effect, its role in the force balance changes only the wind's speed and not its direction.)



a) On the globe diagram, identify the regions where the air is warmest and coldest at Earth's surface by shading them red and blue respectively.

b) What controls the difference in surface air temperature between those regions?

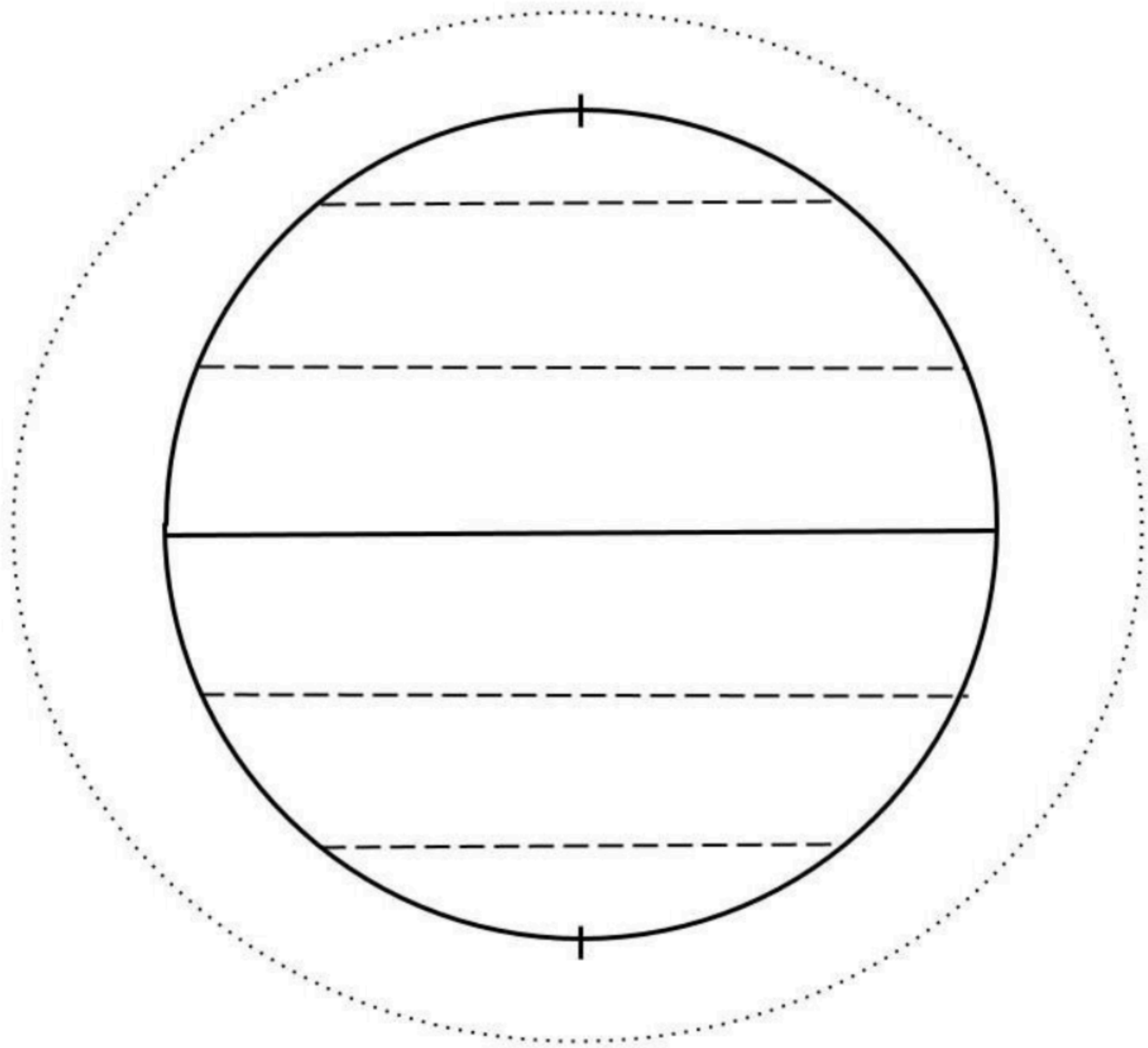
c) Now label your hot and cold regions (latitude bands) with surface H or L, based on what you know about how heating changes the air's surface pressure.

d) Draw arrows showing the wind directions between the surface H and L zones. Remember that the wind direction is the same as the PGF in this model!

e) In the atmosphere cross-section (space on the diagram between the inner solid and dashed outer circles), add arrows showing where air must rise and sink. (How do these locations relate to where you have identified high and low temperature? High and low surface pressure? High and low pressure aloft?)

f) Complete the convection cell in the atmosphere cross-section by drawing the pattern of winds between the H and L zones, aloft as well as at the surface.

4) <u>The Ferrel model: a closer approximation of global circulation on the actual Earth</u>
This model is not quite "reality" either (it ignores the complications of ocean vs. land, seasonal changes and other details), but it is a recognizable approximation of wind and pressure patterns that actually occur. First, notice that each hemisphere has three convection cells, rather than just one. The boundaries between the convection cells are shown (dashed lines on the globe), but it is up to you to fill in the details!



a) First identify latitudes that correspond to surface H and L. Note: The H's and L's that you identified in the Hadley model are still correct; you just need to fill in a few gaps!

b) In the atmosphere cross-section, complete the convection cells by showing surface winds, flow aloft, H's and L's aloft and locations of rising and sinking air.

c) Now add surface winds to the globe for each cell, but don't just draw them straight from H to L: also show how their paths curve due to the Coriolis effect.

5) Global circulation and storm tracks
   Look at the National Hurricane Center map summarizing the 2021 hurricane season in the Atlantic Basin (or, if you prefer, at its 2022 map). Once you have gotten oriented to patterns in the Atlantic Basin (storms that affect the East and Gulf Coasts of North America) by looking at a single year, you will generalize your observations to make and test predictions about hurricane tracks elsewhere in the world.
   a) What is the latitude range in which most of these tropical storms/hurricanes initially form? (There are a few exceptions; focus on the overall pattern.)

   b) What is the initial travel direction for these storms, in general?

   c) Notice that many of the longer storm tracks show a curvature, and that such tracks all curve at about the same latitude. What latitude is it? Give your answer as a range.

   d) Can you relate the curvature in the storm tracks to global convection patterns, including the predominant direction of surface winds in each of the cells in the Ferrel model?

   e) Predict how and where storm tracks will develop in at least one other ocean basin in the northern hemisphere (say, the North Pacific Ocean) and at least one in the southern hemisphere (say, the Southern Indian Ocean). Which way will storms initially start traveling? If the storm tracks curve, at what latitude should it happen, approximately, and what direction will the storms travel after reaching that latitude?

Now visit NOAA's interactive map of historic hurricane tracks and start exploring. I recommend starting with some of the quick links from the main page, such as "major storms of the past decade," to get a sense of how the map works, and then trying your own searches, using the search bar at the top of the map.

   f) To test your predictions from (e), start typing the names of the ocean basins you chose (e.g., Indian Ocean → choose North or South, etc.) and observe the general patterns. Were you correct, or are there any surprises?

   g) You may also enjoy searching for individual storms you already know about. Once the search results load (it may take a few minutes depending on your query), clicking on individual storm tracks on the map or on a storm's name on the sidebar will load additional details on both the map and sidebar, including dates and accompanying changes in the storm's strength. Did you discover any interesting or surprising patterns, examples or exceptions?