Lab 8 for GEOL 1147 (Introduction to Meteorology Lab)

I. Introduction

In this lab you will explore the forces which act on air parcels in the atmosphere. These forces are responsible for driving the observed winds and creating weather systems. Although the mathematics used to describe atmospheric motions can become very complex, the basic principles that govern these motions can be easily understood.

Once an understanding of the forces that act on the atmosphere is achieved you will be able to explain features of the atmosphere which you have likely observed in your daily activities. An example of this is the fact that low pressure systems are often accompanied by cloudy, stormy weather.

II. Basic Forces in the Atmosphere

There are **four** basic forces that act on air parcels in the atmosphere. These forces can be subdivided into those that act on air parcels that are both at rest (not moving) or in motion, and those that act only on air parcels which are moving. The forces that act on an air parcel, regardless of whether or not it is moving, are the **force of gravity** and the **pressure gradient force**. Forces that act on an air parcel only when the parcel is in motion include the **Coriolis force** and the **frictional force**. These latter two forces increase in strength as the velocity of the air parcel increases.

When a force acts on any object it creates an acceleration. An acceleration can be in the form of a change in speed and/or a change in direction of the object's motion. If two forces act on an object in opposite directions and with equal strength, then the object experiences no acceleration, since the two forces exactly balance each other. Only when the sum of all of the forces acting on an object is non-zero will the object accelerate. When the sum of forces acting on an object is zero then the object either remains at rest (if it was initially at rest) or continues to move in a straight line at a constant speed, if it was initially in motion.

Of the four forces that act on parcels in the atmosphere, only the force of gravity does not directly influence horizontal atmospheric motions. The **force of gravity** pulls the atmosphere down towards the center of the Earth and prevents the air molecules from escaping to space, as may well have happened on less massive solar system objects like Mercury and the Moon.

The **pressure gradient force** (PGF) arises when there are *horizontal* differences in air pressure. This force acts in such a way that it accelerates air from regions of higher pressure towards regions of lower pressure. This is the primary force that initiates atmospheric motions. If the atmosphere is assumed to be initially at rest, and a constant pressure gradient force exists throughout the atmosphere, then the air will start to move from regions of higher pressure towards regions of lower pressure. Initially no other horizontal forces will act on the air because there is no motion. (Recall that the Coriolis and friction forces require motion before they can act).

The pressure gradient force is stronger when the pressure changes by a large amount over a small distance and is weaker when the pressure varies only slightly over large distances. The strength of the pressure gradient force can be estimated by looking at weather maps. On certain weather maps lines of constant pressure, called ***isobars***, are drawn to illustrate the pressure distribution at a given height in the atmosphere, so that regions of high and low pressure are discernible. Where these lines are packed closely together the pressure gradient force is large. Where the lines are widely spaced the pressure gradient force is small. In both cases the pressure gradient force is perpendicular to the isobars and points towards lower pressure. When scientists graphically display forces on a diagram, they draw an arrow pointing in the direction that the force is acting (for the pressure gradient force the arrow would point from higher pressure towards lower pressure). The length of the arrow is used to represent the strength, or magnitude, of the force. In the example above, the arrow used to represent the pressure gradient force would be longer in the region of closely spaced isobars and shorter in the region where the isobars are spaced further apart.

The **Coriolis force** is an apparent force that is caused by the rotation of the Earth. The laws which govern all motions assume that the frame of reference used to describe the motion is "fixed" and not moving. For the wind, we describe the motion relative to the surface of the Earth, so that when a meteorologist reports that the wind speed is 25 kts, it means that the wind is moving at a speed of 25 kts *relative* to the surface of the Earth. As the Earth is rotating, the frame of reference used to describe atmospheric motions is *not* fixed, and additional forces must be used to describe the motion. The additional force required to describe atmospheric motions is the **Coriolis force**. This force always acts perpendicular to the direction in which the air is moving, and is directed to the right of this direction in the Northern hemisphere and to the left in the Southern hemisphere. For example, if a southerly wind is observed (the wind is blowing out of the south towards the north) the Coriolis force acts towards the east in the Northern hemisphere, and towards the west in the Southern hemisphere. We are interested not only in the direction of the Coriolis force, but also in its magnitude. The magnitude of the Coriolis force increases as the wind speed increases. In addition, for the same wind speed, the magnitude of the Coriolis force becomes larger as you move polewards, and decreases as you move towards the equator. At the equator the magnitude of the Coriolis force is zero.

The final force that acts on the atmosphere is that of **friction**. As you know from everyday experiences, friction acts to slow down a moving object. The same is true in the atmosphere. A force that slows down an object must act in a direction opposite to the motion. For the example above, the southerly wind will have a friction force that is directed form the north towards the south (opposite to the air's motion from south to north). The magnitude of the friction force increases as the wind speed increases and as the roughness of the surface increases. A mountainous region will have a greater roughness compared to a flat field of wheat, which will in turn have a greater roughness than a smooth surface of water. For these three types of surfaces and for a fixed wind speed, the friction force will be largest over the mountainous terrain and smallest over the smooth water.

III. Geostrophic Balance

Geostrophic flow occurs in the troposphere when the only forces acting on the atmosphere are the pressure gradient and the Coriolis forces, and they are in balance. This happens frequently at altitudes more than a kilometer or so above the surface, where frictional forces are essentially non-existent. Lower down, close to the surface in the so-called *planetary boundary layer*, the force of friction must be considered.

Initially, it may be puzzling to understand how atmospheric motion is possible if the pressure gradient and Coriolis forces are exactly balanced. To understand this phenomenon, let's assume that the atmosphere is initially at rest and that there is a constant pressure gradient force acting throughout the atmosphere. An air parcel initially at rest will begin to accelerate due to this pressure gradient force. The pressure gradient force accelerates the air from regions of higher pressure towards regions of lower pressure. Remember that the Coriolis force only acts on air that is already in motion, and so it is zero when the air is at rest. Once the pressure gradient force begins to accelerate the air, the Coriolis force will start to influence the motion. Initially the wind speed will be small and thus so will the Coriolis force. This small Coriolis force will still start to deflect the wind towards the right of its initial motion, in the Northern hemisphere. As the wind continues to accelerate, the Coriolis force will become larger, even though the pressure gradient force remains constant. Eventually the wind speed will be sufficiently large for the Coriolis force to have deflected the air parcel through 90° to the right. The magnitude of the Coriolis force will then be exactly equal to that of the pressure gradient force. The two forces will be directed in opposite directions, so there will be no net acceleration on the air and it will continue to move in a straight line. In order for these two forces to be directed in opposite directions the wind must be blowing such that lower pressure is to its left and higher pressure to its right (looking downwind). This is because the Coriolis force always acts to the right of the wind direction in the Northern hemisphere and that the pressure gradient force is always directed towards lower pressure. Thus, lower pressure must be to the left of the wind.

For a circular pattern of isobars, the geostrophic flow will be directed counterclockwise around a low pressure center and clockwise around a high pressure center, in the Northern hemisphere. The opposite directions apply in the Southern hemisphere.

For certain applications meteorologists will produce maps on a constant pressure surface rather than at a constant height. Recall that constant height maps are marked with lines of equal pressure (isobars). Constant pressure maps are instead labeled with lines of constant height. The height of a pressure surface in the atmosphere will vary with location. As an example, the height of the 500 mb surface is lower towards the poles than it is towards the equator. The lines on a constant pressure map can be interpreted in the same way that lines on a topographic map are interpreted. An important feature of these two map types is that they have the same pattern if drawn for similar locations in the atmosphere and thus lines of constant height can be interpreted in the same way as isobars. The pressure gradient force will be directed towards lower heights and will have a larger magnitude when the height contours are more tightly packed. A geostrophic wind drawn on a constant pressure map will be directed such that lower heights are to the left of the wind direction, in the Northern hemisphere and the geostrophic wind speed will increase as the height contours become more closely spaced.

IV. Flows influenced by friction

Now consider a flow that is in geostrophic balance that begins to be affected by friction. The friction force will decrease the wind speed from the value it would be if no friction were present, so the wind speed will become less than the geostrophic value. As the wind speed decreases, the Coriolis force must also consequently decrease. The pressure gradient force remains unchanged however, and will therefore now have a larger magnitude than the Coriolis force, so that the wind will be disproportionately influenced by the pressure gradient force, and turn towards lower pressure. Whenever friction acts on the atmosphere the wind will be directed at least partially towards regions of lower pressure and away from regions of higher pressure. As the roughness of the surface increases, the friction force for a given wind speed also increases, and the wind has a larger component across the isobars (height contours) towards lower pressure (heights). You can explore force interactions at
http://profhorn.meteor.wisc.edu/wxwise/kinematics/testwind.html

As noted previously, geostrophic flow circulates counterclockwise around a low pressure center in the Northern hemisphere, paralleling the isobars. When friction starts to influence this flow, the winds are still directed in a counterclockwise sense, but now spiral in towards the center of low pressure. Similarly, winds affected by friction spiral outwards from a center of high pressure in a clockwise fashion.

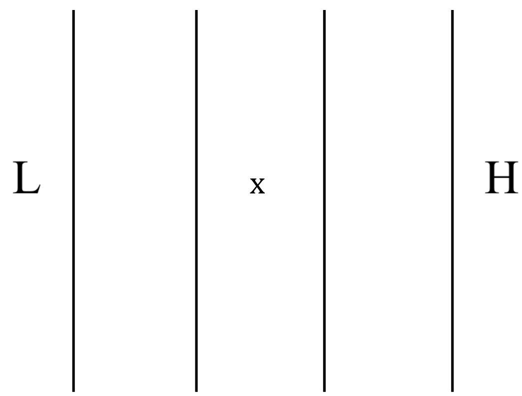
The flow of low level air inward toward low pressure centers and outward from high pressure centers causes vertical motion. As air spirals into a low pressure center, the air that accumulates in the center of the low must be displaced. Since this *convergence* into low pressure centers only occurs near the surface of the Earth, the air cannot be displaced down into the surface, and so it must rise. The opposite occurs with a high pressure center. Air *diverges* away from the high pressure center, and since this air cannot come from the surface, it enters the circulation from aloft by descending down into the high pressure center. Therefore, <u>low pressure centers</u> are characterized by <u>rising</u> motion and <u>high pressure centers</u> are characterized by <u>sinking</u> motion.

When air is forced to rise it cools, resulting in an increase in relative humidity. If the air is forced to rise sufficiently, the relative humidity will reach 100%, condensation will occur, clouds will form, and precipitation may occur. Since low pressure centers are characterized by rising motion, they are therefore often associated with clouds and precipitation. In regions around high pressure centers the air is sinking. Air that is forced to sink becomes warm and its relative humidity decreases. Therefore regions of high pressure are characterized by clear skies and fair weather.

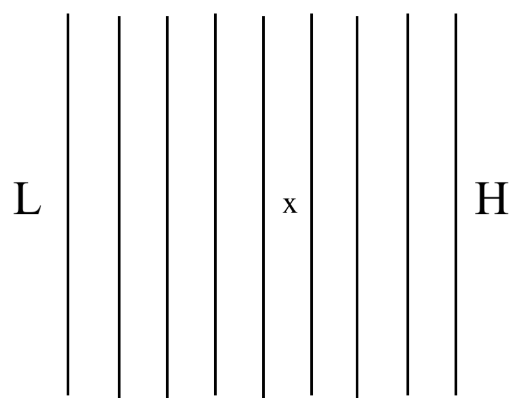
V. Exercises

1. Draw arrows that represent the pressure gradient force at the marked locations ("x") on the maps below. *Remember, the pressure gradient force always acts at right angles to the isobars.* The contours (lines) represent isobars on a constant height map. Indicate the direction of the pressure gradient force with an arrow and represent the *magnitude* of the force by the *length* of the arrow. Make sure that the magnitude of your forces (i.e., the length of your arrows) for each part of this problem are consistent with each other part of the problem, given on the next page.

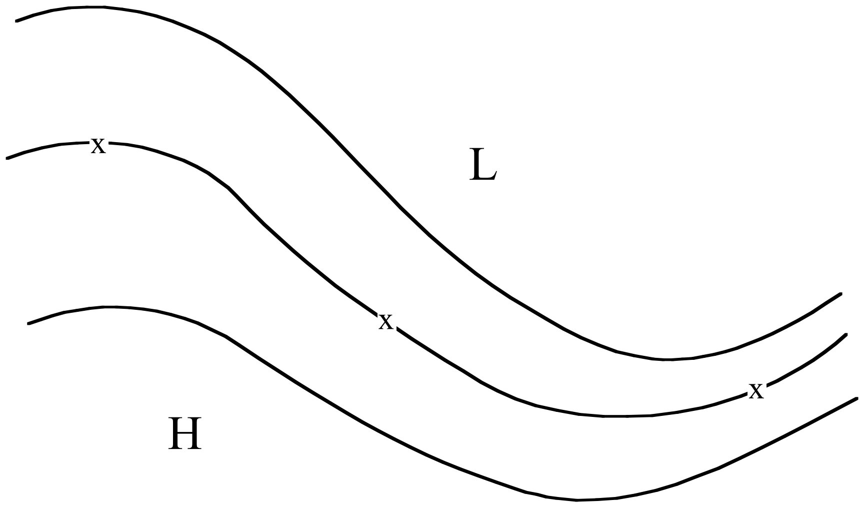
1a.



1b.



1c.



2a. Assume that the wind speed is 20 m s^{-1} at both 60°N and 25°N. At which of these two latitudes is the Coriolis force that acts on the wind largest?

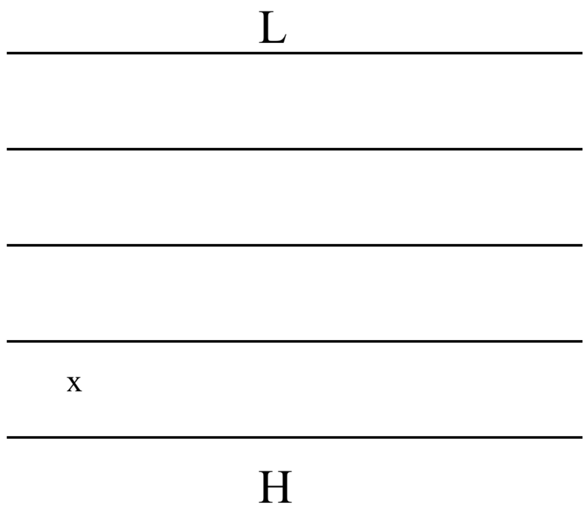
2b. Why?

2c. What is the direction of the Coriolis force on the wind at the two latitudes from problem 2a if the wind is blowing from the west at both locations?

2d. What would your answer to problem 2c be if the latitudes are in the Southern hemisphere?

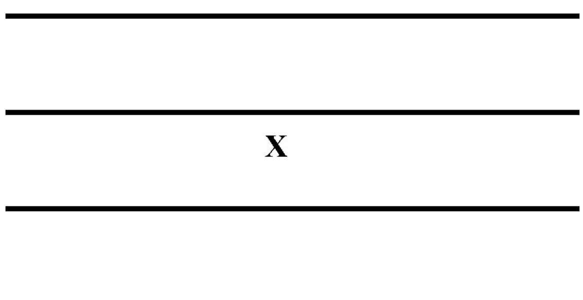
2e. If there is a 20 m s^{-1} wind blowing at the equator, what is the magnitude of the Coriolis force? Why?

3. If the air is in the geostrophic balance, draw the path that the air parcel will follow. Mark the *direction* and *magnitude* of the pressure gradient and Coriolis forces. Draw the map for the northern hemisphere.

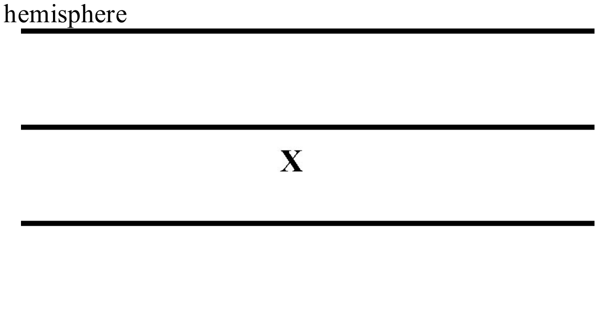


4. For each problem below, draw a picture that illustrates the direction of the pressure gradient and Coriolis forces, and the location of the low and high pressure centers for the given geostrophic wind directions. Assume that north is at the top of the page.

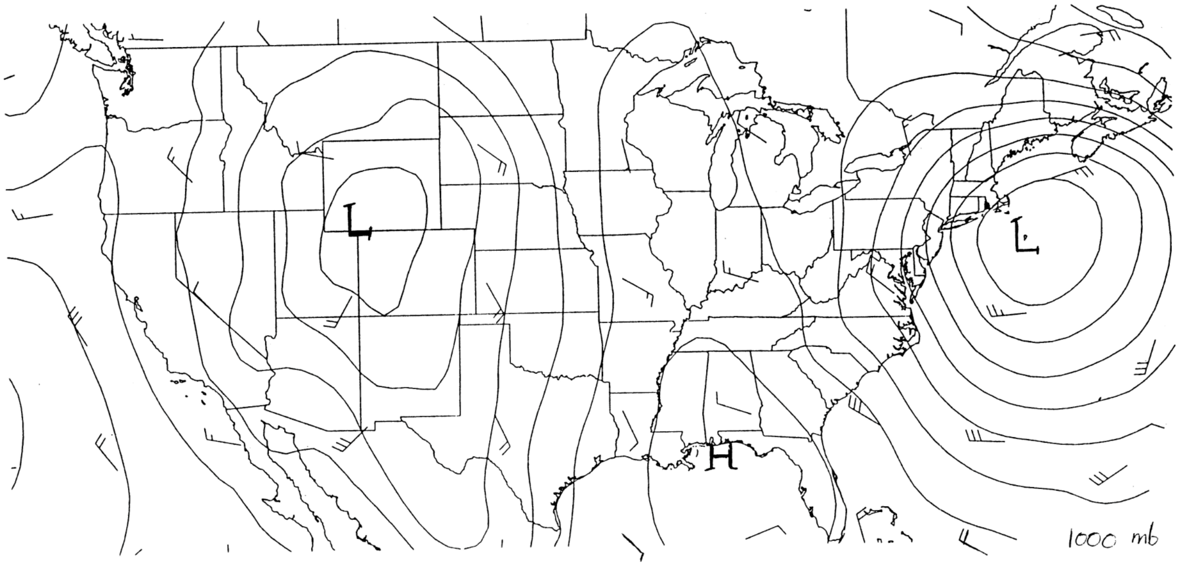
4a. West wind, Northern hemisphere



4b. West wind, Southern hemisphere



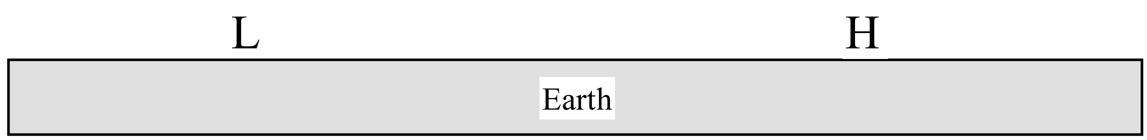
5. Use the map of the 1000 mb height contours and wind vectors below to answer the following question.



Height on 1000 mb surface

Explain why the wind vector plotted in southeastern Utah is directed nearly perpendicular to the height contours in that region, while the wind vector plotted south of the low pressure center in the Atlantic Ocean is nearly parallel to the height contours.

6a. On the vertical cross-section of the atmosphere drawn below, indicate the horizontal wind direction expected near the surface of the Earth and the vertical motions expected above each pressure center, indicated by H and L. Then, complete the circulation. Assume that the tropopause acts as an ‘upper lid’ to the motion.



6b. Based on the air flows you have drawn in the figure in problem 6a, explain why cloudy skies are associated with low pressure centers near the surface of the Earth.

6c. Based on the air flows you have drawn in the figure in problem 6a, explain why clear skies are associated with high pressure centers near the surface of the Earth.