Lecture 5

Pressure and Winds

5.1 The Concept of Pressure

The atmosphere contains a tremendous number of gas molecules being pulled toward Earth by the force of gravity. These molecules exert force on surfaces with which they are in contact, and the amount of that force exerted per unit of surface area is **pressure**.

The unit of pressure in physics is Pascal (Pa) but in meteorology, the preferred unit is mb, which is equal to hectopascal (hPa). (1 mb = 1 hPa = 100 Pa.)

Any instrument that measures pressure is called a *barometer*. There are many types such as mercury barometers and aneroid barometers.

In Fig. 5.1, there are closed containers of air. The air molecules are in continuous movement and exert a pressure on the interior walls of the container (see Fig. 5.1 a).

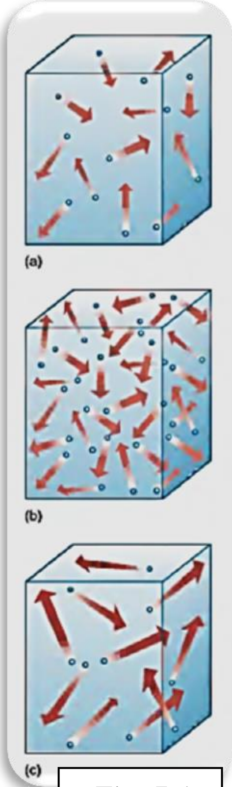


Fig. 5.1

We can increase the pressure inside the container with two ways:

The first way is by increasing the density of the air either by pumping more air into the container or by decreasing the volume of the container (see Fig. 5.1 b). The second is by increasing the air temperature , in which case the molecules exert higher pressure because they are moving more rapidly (see Fig. 5.1 c). Thus, pressure reflects both the density and temperature of the gas.

Partial pressure is the pressure which exerted by a mixture of gases. The total pressure exerted is equal to the sum of the partial pressures (Dalton's law).

On Earth, the container is surrounded by the atmosphere, which exerts pressure on the exterior walls. The pressure at any point reflects the mass of atmosphere above that point. We most commonly measure air pressure as it exists at the surface (sirface pressure), but meteorologists are also concerned with air pressure at heights above the surface. As we go upward through the atmosphere, the mass of atmosphere above necessarily decreases, so pressure must also decrease. Not that pressure is unique among atmospheric variables in that it always decreases vertically. Other variables (such as temperature, moisture, and density) do not necessarily behave this way.

Despite the fact that the atmosphere is pulled downward by the force of gravity, air pressure is exerted equally in all directions.

5.2 Vertical and Horizontal Changes in Pressure

We need to measure and compare the differences in pressure that arise in different locations, since these differences produce horizontal movements of air (winds). We know that elevation varies from place to place. (Recall that high elevations have lower pressure; Why?). If we used just surface measurements for comparisons, it would be impossible to separate the effects of elevation from the true pressure differences that lead to wind. Hence, meteorologists use the concept of sea level pressure, which is the pressure that would exist if the observation point were at sea level. Sea level pressure allows us to compare pressure at different locations.

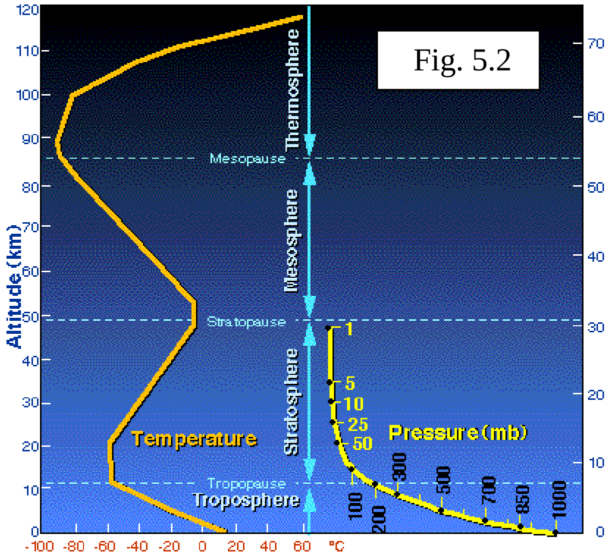


Fig. 5.2

Pressure does not decrease with height at a uniform rate. Instead, it decreases most rapidly at low elevations and gradually tapers off at greater heights (see Fig. 5.2).

Though surface pressure also varies from place to place, horizontal pressure differences are very small compared to vertical differences. For example, a horizontal pressure difference of 10 hPa between two cities such as Cairo and Baghdad may causes a dust storm but the same value of pressure can be achieved in just 50 m vertically and causes nothing

5.3 The Equation of State

The temperature, density, and pressure are related to one another via the equation of state (also called the ideal gas low), $p = \rho \, R \, T$

p is pressure (in Pascals), ρ is density (in kg/m^3), R is a the gas constant which is equal to 287 J kg^{-1}K^{-1}, and T is temperature (in Kelvins).

The equation tells us that if the air density increases while temperature is held constant, the pressure will increase. Similarly, at constant density, an increase in temperature leads to an increase in pressure.

5.4 The Distribution of Pressure

The distribution of the pressure (SLP) across the globe is a highly variable characteristic of the atmosphere. Meteorologists plot lines called *isobars* on a weather map. Each isobar is drawn so that it connects points having exactly the same sea level pressure. The spacing between the isobars indicates the strength of the pressure gradient. The Fig. 5.3 shows a surface weather chart. The letter L refers to a low-pressure system and H refers to a high-pressure system. As it is clear, the high-pressure gradient is existed in the northeast of United States where the isobars are more closed to each other.

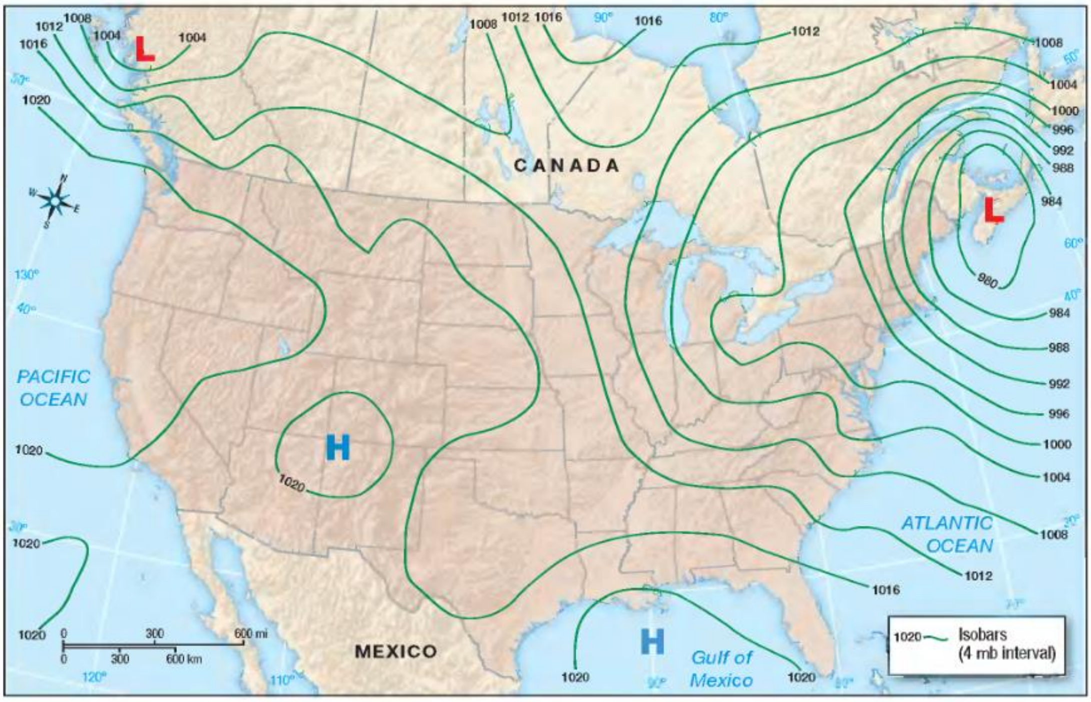


Fig. 5.3 a surface weather chart

5.5 Pressure Gradients

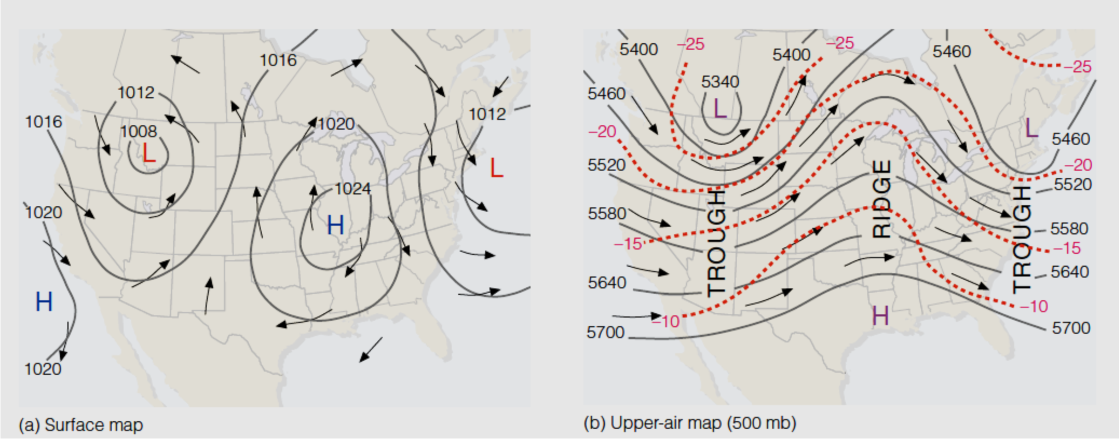
Pressure gradients provide the impetus for the movement of air we call *wind*. If the air over one region exerts a greater pressure than the air over an adjacent region, the higher-pressure will spread out toward the zone of lower pressure as wind. The pressure gradient gives rise to a force called the *pressure gradient force* that sets the air in motion. In the vertical direction, also there is a *vertical gradient force* caused by the decreasing of pressure with height. The wind speed is measured by anemometers.

5.6 Hydrostatic Equilibrium

Hydrostatic equilibrium refers to the balance between the vertical gradient force directing upward and the gravitational force directing downward. This balance keeps the air in contact with the earth surface with no significant wind in the vertical direction. When the gravitational force slightly exceeds the vertical pressure gradient force, downward motions result. On the other hand, the upward-directed pressure gradient force sometimes greatly exceeds the gravitational force, generating updrafts which may associated with powerful thunderstorms. The balance between the two forces can be expressed by the hydrostatic equation: $\frac{\Delta p}{\Delta z} = -\rho\, g$.

5.7 Upper-Air Charts

Fig. (5.4. b) shows a simplified upper-air chart for the same day as the surface map in Fig. (5.4. a). The upper-air map is a constant pressure chart because it is constructed to show height variations along a constant pressure (isobaric) surface. This particular map shows height variations at a pressure level of 500 mb (which is about 5600 m above sea level). Hence, this map is called a 500 mb map. The solid dark lines on the map are contour lines, i.e., lines that connect points of equal elevation above sea level. Although contour lines are height lines, they illustrate pressure much like isobars do. Consequently, contour lines of low height represent a region of lower pressure, and contour lines of high height represent a region of higher pressure. Notice on the 500-mb map that the contour lines typically decrease in value from south to north. Observe that colder air is generally to the north and warmer air to the south, and recall from our earlier discussion that cold air aloft is associated with low pressure, warm air aloft with high pressure. The contour lines are not straight, however, they bend and turn, indicating ridges (elongated highs) where the air is warmer and indicating depressions, or troughs (elongated lows) where the air is colder. The arrows on the 500 mb map show the wind directions tend to flow parallel to the contour lines. Surface and upper-air charts are valuable tools for the meteorologist. Surface maps describe where the centers and high and low pressure are found, as well as the winds and weather associated with these systems. The upper-level winds not only determine the movement of surface pressure systems but, they determine whether these surface systems will intensify or weaken.



(a) Surface map (b) Upper-air map (500 mb)

Fig. 5.4

5.8 Forces Affecting the Speed and Direction of the Wind

We have already learned that horizontal differences in atmospheric pressure cause air to move and, hence, the wind to blow.

1. *Pressure Gradient Force* (which was explained earlier)

If we compute the amount of pressure change that occurs over a given distance, we have the pressure gradient; thus

$$\text{Pressure gradient} = \frac{\text{difference in presssure}}{\text{distance}}$$

In Fig. 5.5, the pressure gradient between points 1 and 2 is 4 mb per 100 km. Suppose the pressure in were to change, and the isobars become closer together. This condition would produce a rapid change in pressure over a relatively short distance, or what is called a steep (or strong) pressure gradient. However, if the pressure were to change such that the isobars spread farther apart, then the difference in pressure would be small over a relatively large distance. Notice in the figure that when differences in horizontal air pressure exist there is a net force acting on the air. This force, called the pressure gradient force (PGF), is directed from higher toward lower pressure at right angles to the isobars. The magnitude of the force is directly related to the pressure gradient. Steep pressure gradients correspond to strong pressure gradient forces and vice versa.

If the pressure gradient force were the only force acting upon air, we would always find winds blowing directly from higher toward lower pressure. However, the moment air starts to move, it is deflected in its path by the Coriolis force.

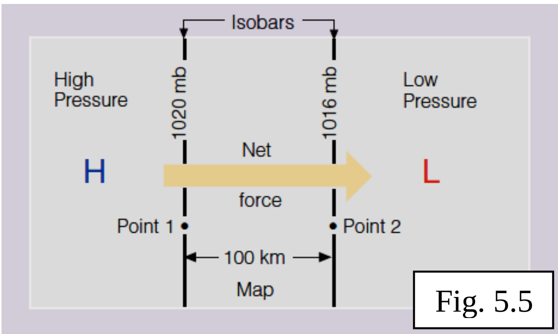


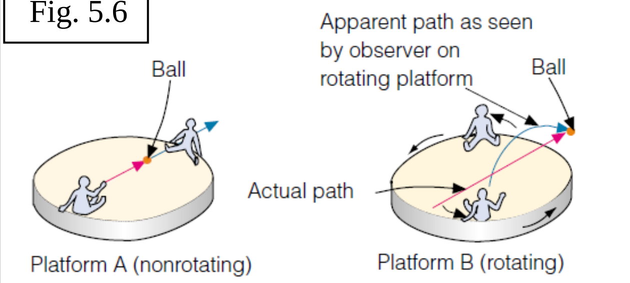
Fig. 5.5

2. *Coriolis Force*

The Coriolis force describes an apparent force that is due to the rotation of the earth. To understand how it works, consider two people playing catch as they sit opposite one another on the rim of a merry-go-round (see Fig. 6.13, platform A). If the merry-go-round is not moving, each time the ball is thrown, it moves in a straight line to the other person.

Suppose the merry-go-round starts turning counterclockwise— the same direction the earth spins as viewed from above the North Pole. If we watch the game of catch from above, we see that the ball moves in a straight-line path just as before. However, to the people playing catch on the merry-go-round, the ball seems to veer to its right each time it is thrown, always landing to the right of the point intended by the thrower (see Fig. 5.6 B).

Fig. 5.6



This perspective is due to the fact that, while the ball moves in a straight-line path, the merry-go-round rotates beneath it; by the time the ball reaches the opposite side, the catcher has moved. To anyone on the merry-go-round, it seems as if there is some force causing the ball to deflect to the right. This apparent force is called the Coriolis force.

The Coriolis force causes the wind to deflect to the right of its intended path in the Northern Hemisphere and to the left of its intended path in the Southern Hemisphere.

As the wind speed increases, the Coriolis force increases; hence, the stronger the wind, the greater the deflection. Additionally, the Coriolis force increases for all wind speeds from a value of zero at the equator to a maximum at the poles. This phenomenon is illustrated in Fig. 6.14 where three aircraft, each at a different latitude, are flying along a straight-line path, with no external forces acting on them. The destination of each aircraft is due east and is marked on the illustration in Fig. 6.14a. Each plane travels in a straight path relative to an observer positioned at a fixed spot in space. The earth rotates beneath the moving planes, causing the destination points at latitudes 30° and 60° to change direction slightly—to the observer in space (see Fig. 5.7). To an observer standing on the earth, however, it is the plane that appears to deviate. The amount of deviation is greatest toward the pole and nonexistent at the equator. Therefore, the Coriolis force has a far greater effect on the plane at high latitudes (large deviation) than on the plane at low latitudes (small deviation). On the equator, it has no effect at all. The same is true of its effect on winds. In summary, to an observer on the earth, objects moving in any direction (north, south, east, or west) are deflected to the right of their intended path in the Northern Hemisphere and to the left of their intended path in the Southern Hemisphere.

The amount of deflection depends upon (the rotation of the earth, the latitude, the object's speed).

In addition, the Coriolis force acts at right angles to the wind, only influencing wind direction and never wind speed.

The Coriolis "force" behaves as a real force, constantly tending to "pull" the wind to its right in the Northern Hemisphere and to its left in the Southern Hemisphere. Moreover, this effect is present in all motions relative to the earth's surface. However, in most of our everyday experiences, the Coriolis force is so small (compared to other forces involved in those experiences) that it is negligible and, contrary to popular belief, does not cause water to turn clockwise or counterclockwise when draining from a sink.

The Coriolis force is also minimal on small-scale winds, such as those that blow inland along coasts in summer. Here, the Coriolis force might be strong because of high winds, but the force cannot produce much deflection over the relatively short distances. Only where winds blow over vast regions is the effect significant.

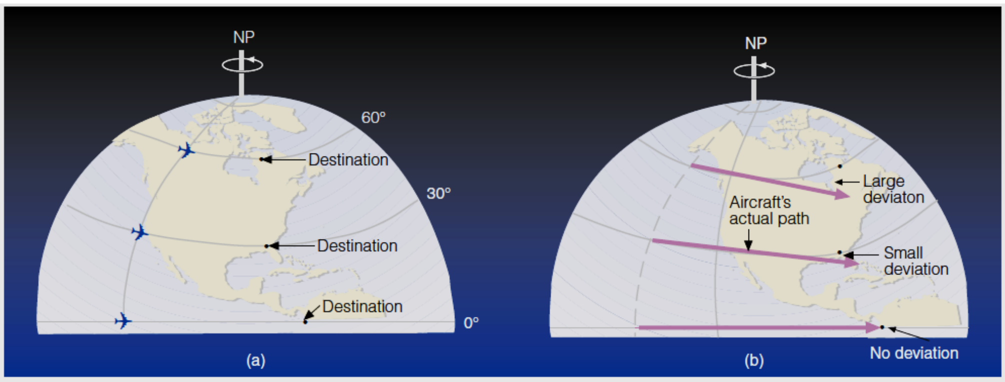
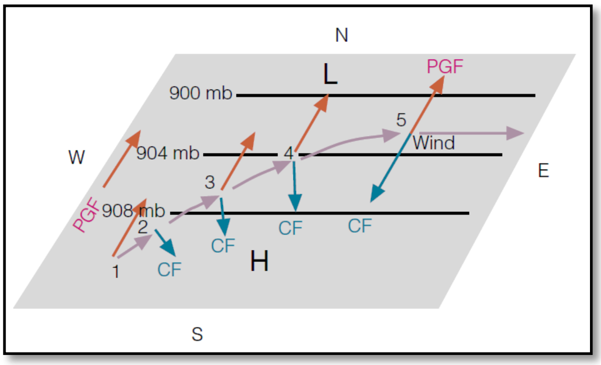


Fig. 5.7.

The geostrophic wind is the wind that results from the balance of horizontal pressure gradient force and the Coriolis force. This wind can be existed at a high altitude and is parallel to the contour lines (or isobars) (see Fig. 5.8).

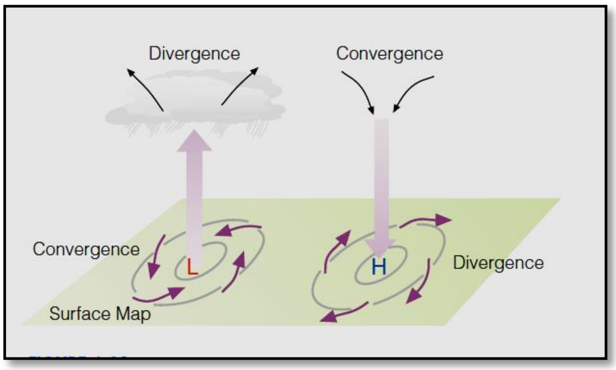
Fig. 5.8



5.9 Convergence and Divergence

Surface winds move outward (diverge), away from the center of a high-pressure area. To replace this laterally spreading air, the air aloft converges and slowly descends (see Fig. 5.9). Again, as long as upper-level converging air balances surface diverging air, the central pressure in the high will not change. (Convergence and divergence of air are so important to the development or weakening of surface pressure systems.)

Fig. 5.9



5.10 Friction force

The other factor that influences the movement of air is friction, the force resisting the movement of a fluid of object as it passes along a surface or an adjacent gas or liquid. Air in contact with the surface experiences frictional drag, which decreases wind speed.

Homework:

1. What is a partial pressure?
2. Why does pressure always decrease with altitude?
3. What is the difference between surface pressure and sea level pressure?
4. What are the equation of state and the hydrostatic equation, and what do they tell us?
5. What two variables determine air pressure?
6. Explain the concept of hydrostatic equilibrium.
7. Explain how air temperature affects the vertical pressure gradient.
8. Briefly describe the movement of air around cyclones and anticyclones in the Northern Hemisphere.