

Lesson 3

The Dynamic Structure of the Atmosphere

Goal

To familiarize you with the factors that affect atmospheric motion including atmospheric pressure, wind, frictional influences, fronts and air masses. To explain how topographical features such as land, water, and mountains affect air movement.

Objectives

Upon completing this lesson, you will be able to do the following:

1. Name and explain three forces that determine wind direction and speed within the earth's friction layer.
2. Explain why wind speed changes with height and why this is important in air pollution studies.
3. Describe the effect that pressure systems have on the transport of air pollution.
4. Identify the two basic properties of an air mass.
5. Distinguish between four different types of fronts.
6. Explain the phenomenon called "frontal trapping."
7. Explain how different types of terrain affect air flow and consequently air pollution dispersion.

Introduction

We are all familiar with the various forms atmospheric motion can take: gentle breezes, thunderstorms, and hurricanes, to name a few. Air moves in an attempt to equalize the air pressure imbalances that develop as a result of variations in insolation and differential heating. Differential heating is the main cause of atmospheric motion on the earth. This lesson will answer your questions about what causes the wind to blow from a certain direction and what causes the general global patterns of air circulation. You will learn how winds aloft behave differently from surface winds and how surface winds are influenced by the earth's topography.

Atmospheric Circulation

Air moves in an attempt to equalize imbalances in pressure that result from differential heating of the earth's surface. While moving from areas of high pressure to low pressure, wind is heavily influenced by the presence or absence of friction. Thus, surface winds behave differently than winds aloft due to frictional forces acting near the earth's surface. The rotation of the earth modifies atmospheric motion but does not cause it, since the atmosphere essentially rotates with the earth. The movement of air helps keep concentrations of pollutants that are released into the air from reaching dangerous levels.

Air Pressure

Even though you can't see it, air has weight. In any gas such as air, molecules are moving around in all directions at very high speeds. The speed actually depends on the temperature of the gas. Air pressure is caused by air molecules (e.g. oxygen, nitrogen) bumping into each other and other things and bouncing off. Air pressure is a function of the number of air molecules in a given volume and the speed at which they are moving. When air is confined within a certain boundary, heating the air increases its pressure and cooling the air decreases its pressure. Forcing air into a smaller space increases air pressure while allowing it to expand into a larger space reduces air pressure.

Air pressure at any location whether it is on the earth's surface or up in the atmosphere depends on the weight of the air above. Imagine a column of air. At sea level, a column of air extending hundreds of kilometers above sea level exerts a pressure of 1013 millibars (mb) (or 1.013 kP). But, if you travel up the column to an altitude of 5.5 km (18,000 feet), the air pressure would be roughly half, or approximately 506 mb (0.506 kP).

Areas of high and low pressure are depicted in Figure 3-1. The roughly concentric circles around the areas of highest and lowest pressure are called isobars, which are lines of equal pressure. Isobars may follow straight lines or form rings as they do around areas of high and low pressure. The pressure readings in the diagram range from 1008 to 1024 millibars (mb).

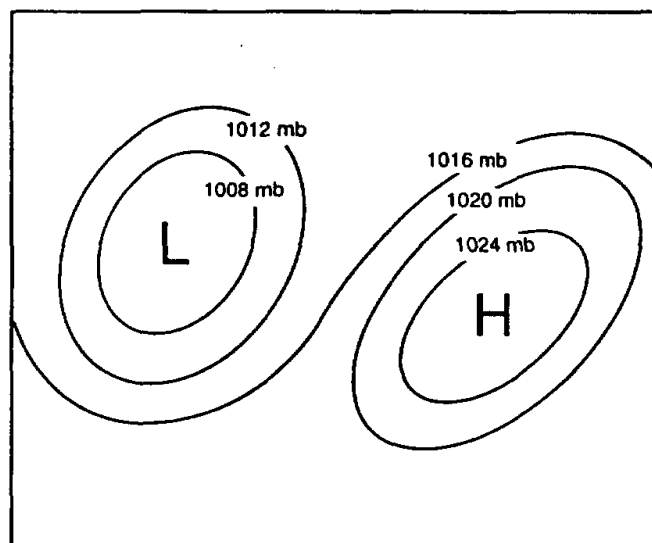


Figure 3-1. Isobars around areas of low and high pressure

Wind

Wind is the basic element in the general circulation of the atmosphere. Wind movements from small gusts to large air masses all contribute to transport of heat and other conditions of the atmosphere around the earth. Winds are always named by the direction from which they blow. Thus a "north wind" is a wind blowing from the north toward the south and a "westerly wind" blows from west to east. When wind blows more frequently from one direction than from any other, the direction is termed the **prevailing wind**.

Wind speed increases rapidly with height above the ground level, as frictional drag decreases. Wind is commonly not a steady current but is made up of a succession of gusts, slightly variable in direction, separated by lulls. Close to the earth, wind gustiness is caused by irregularities of the surface, which create eddies. Eddies are variations from the main current of wind flow. Larger irregularities are caused by convection—or vertical transport of heat. These and other forms of turbulence contribute to the movement of heat, moisture, and dust into the air aloft.

Coriolis Force

If the earth did not rotate, air would move directly from high pressure toward low pressure. However, since the earth does rotate, to an observer standing on the surface of the rotating earth there is an apparent deflection of air. The **Coriolis force** causes this deflection to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The Coriolis force is an apparent force due to the earth rotating under the moving air. Observed from space, this movement of air (or any freely moving object for that matter) would appear to follow a straight line. But to an observer on earth this movement appears to be deflected.

A demonstration of the Coriolis force is shown in Figure 3-2. Imagine a spinning turntable rotating around its center axis like the earth (Figure 3-2a). If you were to hold a ruler still and draw a straight line across the spinning turntable you would see a straight line from your vantage point. If the turntable were the earth, your vantage point would be space. However, the line you would draw on the turntable would actually be curved. So from the turntable's point of view, the line was deflected (Figure 3-2c).

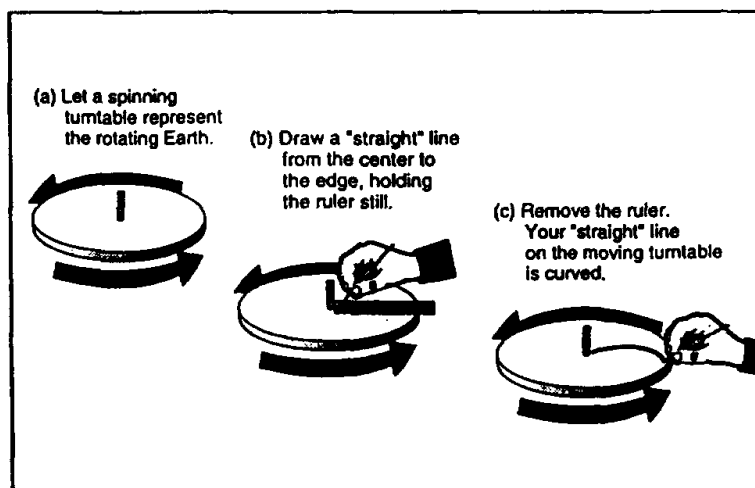


Figure 3-2. The Coriolis force

This is the same thing that happens when the wind blows. This apparent force on the wind:

- Increases as wind speed increases
- Remains at right angles to wind direction (see Figure 3-3)
- Increases with an increase in latitude (i.e., force is greatest at the poles and zero at the equator)

The effect of this deflecting force is to make the wind seem to change direction on earth. Actually, the earth is moving with respect to the wind. As Figure 3-3 shows, winds appear to be deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

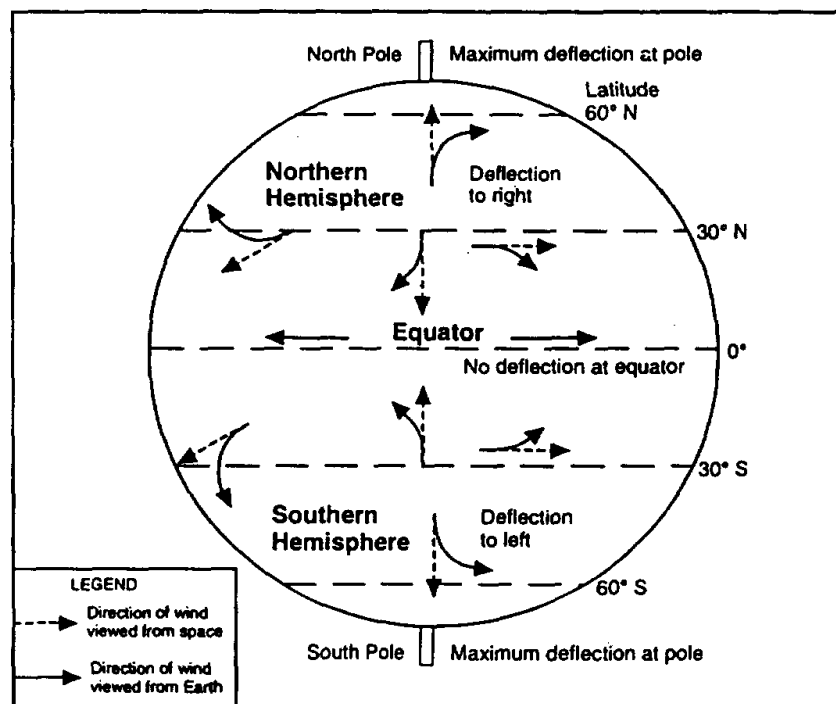


Figure 3-3. The deflection of large-scale winds in the Northern and Southern Hemispheres

Pressure Gradient Force

Wind is caused by nature's attempt to correct differences in air pressure. Wind will flow from areas of high pressure to low pressure. The pressure equalizing force that attempts to move air from high pressure to low pressure is called the **pressure gradient force**.

The **pressure gradient** is the rate and direction of pressure change. It is represented by a line drawn at right angles to the isobars as shown in Figure 3-4. Gradients are steep where isobars are closely spaced. The wind will move faster across steep gradients. Winds are weaker where the isobars are farther apart because the slope between them is not as steep; therefore, wind does not build up as much force.

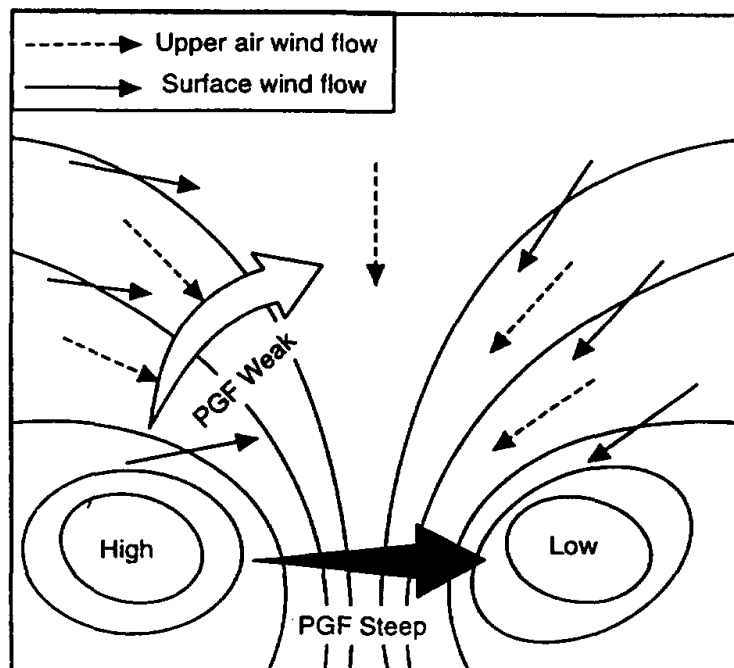


Figure 3-4. Pressure gradients

Figure 3-4 shows that wind moves from areas of high to low pressure, but because of the Coriolis force (effect of the earth's rotation), wind does not flow parallel to the pressure gradient. Also, notice that wind direction at the surface (solid lines) differs from wind direction high above the earth (dotted lines) despite the same pressure gradient forces operating. This is due to frictional forces as explained in the next section.

Friction

Friction, the third major force affecting the wind, comes into play near the earth's surface and continues to be a factor up to altitudes of about 500 to 1000 m. This section of the atmosphere is referred to as the **Planetary or Atmospheric Boundary Layer**. Above this layer, friction no longer influences the wind. The Coriolis force and the pressure gradient force are in balance above the Planetary Boundary Layer. As shown in Figure 3-5, the balanced forces that occur above the layer where friction influences the wind, create a wind that will blow parallel to the isobars. This is called the **geostrophic wind**. In the Northern Hemisphere low pressures will be to the left of the wind. The reverse is true in the Southern Hemisphere.

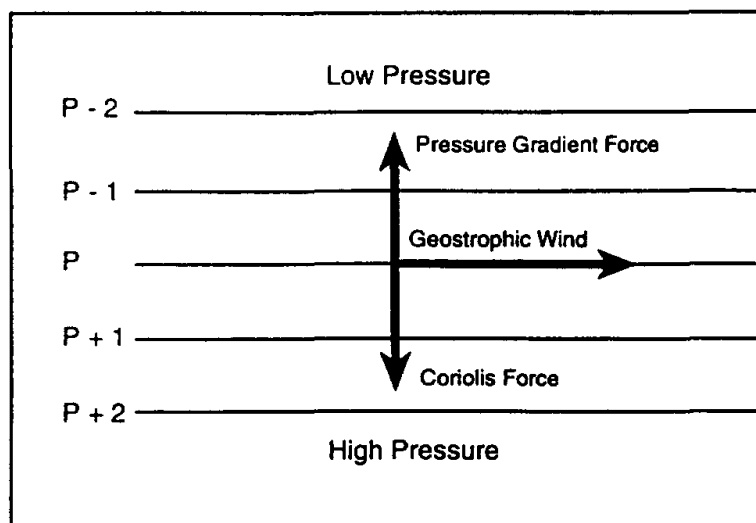


Figure 3-5. Balance of forces resulting in geostrophic wind (Northern Hemisphere)

Within the friction layer, the Coriolis force, pressure gradient force, and friction all exert an influence on the wind. The effect of friction on the wind increases as the wind approaches the earth's surface. Also, the rougher the surface of the earth is, the greater the frictional influence will be. For example, air flow over an urban area encounters more friction than air flowing over a large body of water.

Friction not only slows wind speed but also influences wind direction. Friction's effect on wind direction is due to the relationship between wind speed and the Coriolis force. Remember, the Coriolis force is proportional to wind speed. Consequently, as winds encounter more friction at progressively lower altitudes within the friction layer, wind speeds decrease and so does the Coriolis force. With friction, the Coriolis force lessens in relation to the pressure gradient force; the pressure gradient force no longer exactly balances the Coriolis force as it does with the geostrophic wind above the Planetary Boundary. Instead, the pressure gradient force predominates, turning the wind toward low pressure (see Figure 3-6). The wind direction turns toward low pressure until the resultant vector of the frictional force and the Coriolis force exactly balances the pressure gradient force. As frictional forces become greater, wind directions turn more sharply toward low pressure. This change in wind direction at different altitudes within the friction layer is depicted in Figure 3-7 and is referred to as the **Ekman Spiral**. The turning of the wind's direction lessens with height until friction no longer influences wind flow as in the case of the geostrophic wind.

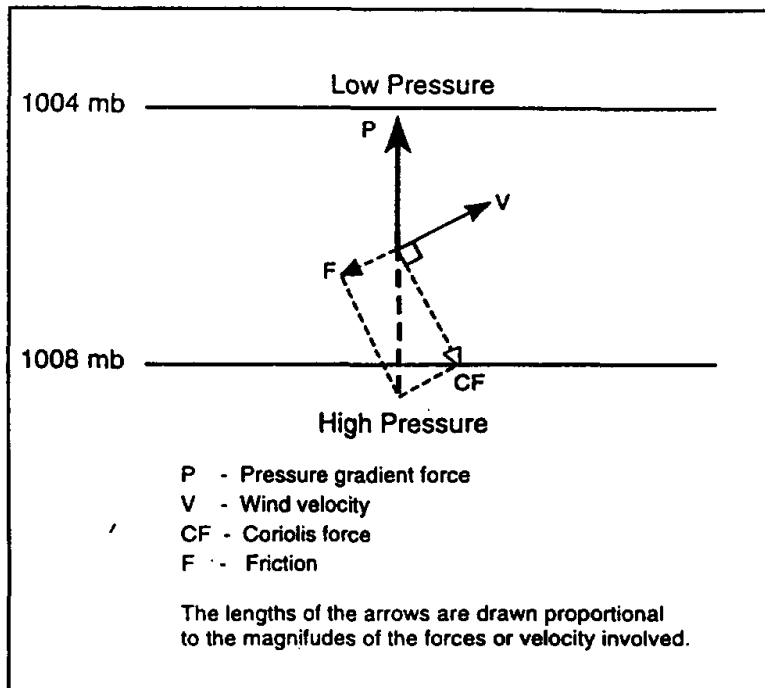


Figure 3-6. The Coriolis force combines with friction to balance the horizontal pressure gradient force

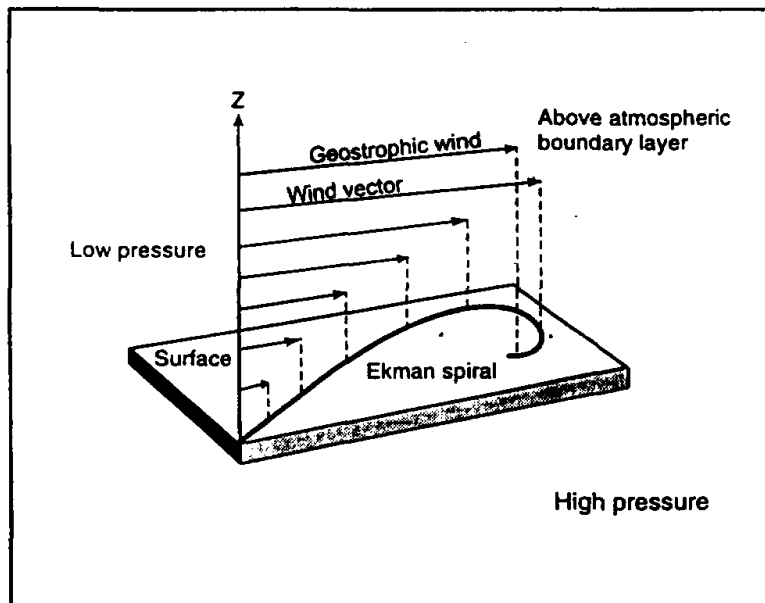


Figure 3-7. The Ekman spiral of wind in the Northern Hemisphere

The effect that friction has on wind has a profound influence on the transport of air pollutants. As a plume of air pollutants rises from a stack it will likely rise through the boundary layer of the atmosphere where friction changes the direction of the wind with height. This will spread the plume horizontally in slightly different directions. Also,

pollutants released at different heights in the atmosphere may move in slightly different directions.

Pressure Systems

The horizontal movement of air is directed by many forces. Surface winds are directed in a *counterclockwise* fashion around low pressure systems (cyclones) in the Northern Hemisphere. This same balance of forces directs air in a *clockwise* fashion around high pressure systems (anticyclones) in the Northern Hemisphere. The resulting air flow associated with pressure systems near the earth's surface is shown in Figure 3-8. At upper levels of the atmosphere where frictional forces are removed, the air moves parallel to the isobars as shown in Figure 3-5.

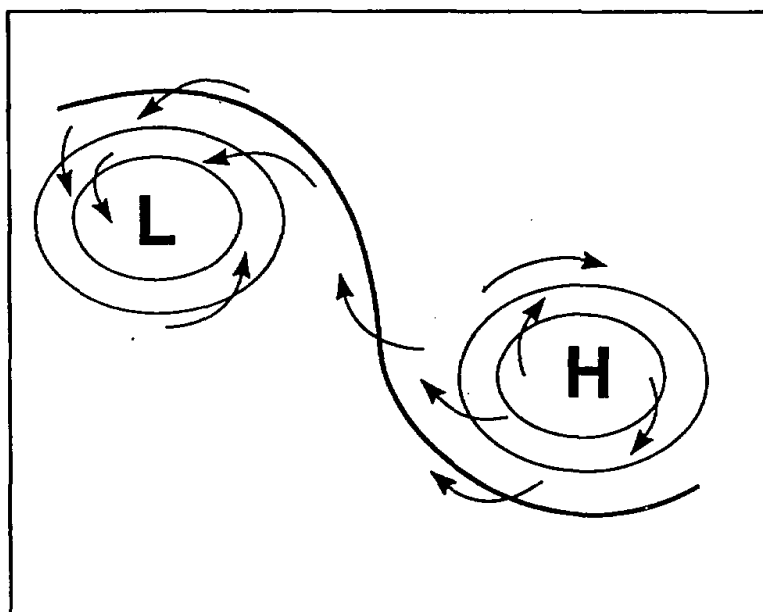


Figure 3-8. Surface air flow around low and high pressure systems

Effects of Pacific High and Bermuda High on Air Pollution

The presence of semipermanent, subtropical anticyclones over the major oceans influence air pollution dispersion in several areas of the world including the continental United States. The Pacific High and Bermuda High are two such examples of large-scale, high pressure systems that affect air quality in southern California and the southeastern U.S. respectively. These high pressure systems are referred to as semipermanent because they shift position only slightly from summer to winter. They are formed from air sinking in the region above the horse latitudes (around 30° latitude). Cold, subsiding (sinking) air aloft is compressed and is heated as it sinks in these areas of high pressure, establishing an elevated temperature inversion. An elevated temperature inversion occurs when a layer of warm air resides over a layer of cooler air, thereby restricting the vertical movement of air. The bottom of this inversion layer generally approaches the surface the further one gets from the center of the anticyclone. For more information about inversions in general and subsidence inversions in particular, see Lesson 4.

Pacific High

On the *eastern* side of these semipermanent anticyclones, the inversion layer is strengthened by the clockwise air flow around the pressure system which brings in air from the north. The air cools from contact with the cool ocean water. This condition plagues southern California which is located on the eastern side of the Pacific High. Temperature inversions, which limit vertical mixing of air pollutants, are common in this area. Thus air pollutants can build up in the shallow layer of the atmosphere under the inversion layer to dangerous levels.

Bermuda High

On the *western* side of the semipermanent anticyclones the conditions are less severe. Clockwise motion of air results in wind flow from the southern tropical areas where the air is warm and moist. Subsiding air in these areas of high pressure can still lead to elevated temperature inversions, but the frequency and strength of these inversions are not as great as those influencing the western coasts of continents, due to the advection of warm air. This situation is typical of the southeastern United States where the Bermuda High, situated in the Atlantic Ocean, influences pollution transport and dispersion in this region.

General Circulation

The general circulation represents the *average* air flow around the world. While winds at any particular time and place may vary widely from the average, studying the average wind flow patterns can help you to identify the predominant circulation patterns at certain latitudes and to understand the causes for these patterns. As you learned in lesson 2, the driving force behind general circulation is the uneven heating of the earth's surface. The equatorial regions receive much more energy from the sun than the polar regions do. Horizontal temperature variations in the atmosphere, caused by unequal heating, leads to pressure differences that drive atmospheric circulation.

Because the global circulation of air is complex, we will start with a simple model that explains how air would circulate without the complications caused by the earth's rotation and its non-uniform surface. If the earth were nonrotating and composed of a uniform solid surface, we would see a very predictable circulation pattern extending from the equator to the poles (see Figure 3-9). Air at the equator, which receives more of the sun's radiation, would be hotter than air at the poles. The air at the equator would be warm and buoyant and would rise due to convection. As the warm equatorial air rises, thunderstorms develop which release more heat, causing the air to continue to rise until it reaches the upper atmosphere. At this point, the air would begin to move toward the polar regions, cooling as it traveled. At the poles, the dense cold air would sink to the surface and flow back toward the equator. In the Northern Hemisphere, the air flow near the surface would always be out of the north because the cooler air from the North Pole would replace the warm air ascending at the equator.

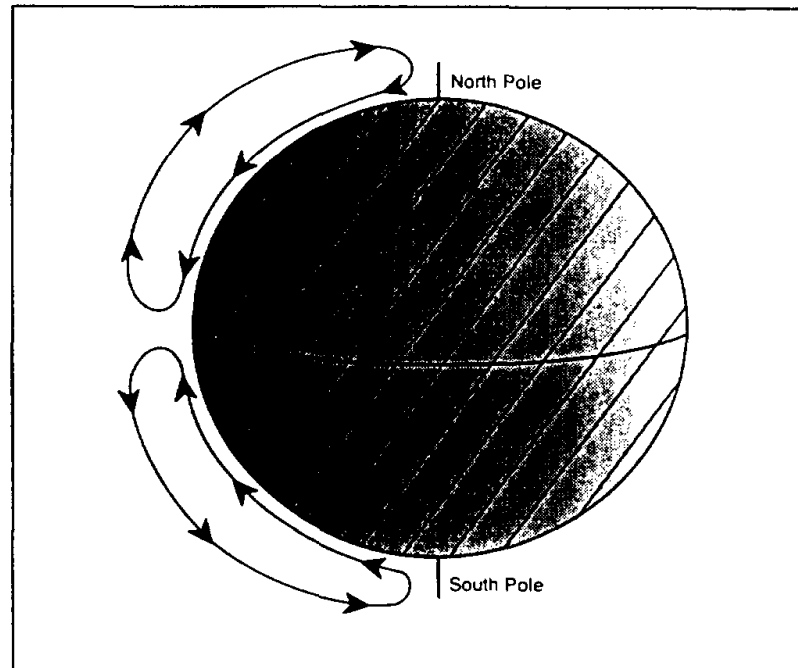


Figure 3-9. Hypothetical planetary air circulation for nonrotating earth of uniform surface

But, the earth does rotate—a fact that changes this relatively simple air flow into a very complex situation. The Coriolis effect is a major factor that explains the actual air flow patterns around the world.

The following explanation for planetary air circulation takes the Coriolis force into account. At the equator, warm air rises and often condenses into huge thunderclouds and storms. Thus a band of low pressure develops around the equator. These thunderstorms liberate heat which drives the air higher in the atmosphere. Here, the air starts to travel laterally toward the poles, cooling as it moves. The air starts to converge or "come together" aloft near the 30° latitudes. The convergence of air causes air to sink or subside at this latitude. This leads to air divergence at the earth's surface. As air sinks in this region, skies are generally cloudless and surface winds are light and variable. The 30° latitudes are referred to as the **horse latitudes** because sailing ships traveling to the New World were often becalmed here. According to legend, as food and supplies diminished, horses were often eaten or thrown overboard in this region.

From the horse latitudes, some of the surface air moves back toward the equator. Because of the Coriolis effect, the winds blow from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. These steady winds are called the **trade winds** because they facilitated sailing ships on their voyages from Europe to America. As you can see in Figure 3-10, the trade winds converge around the equator in a region called the **Intertropical Convergence Zone (ITCZ)**. This converging equatorial air heats and rises, continuing the cycle.

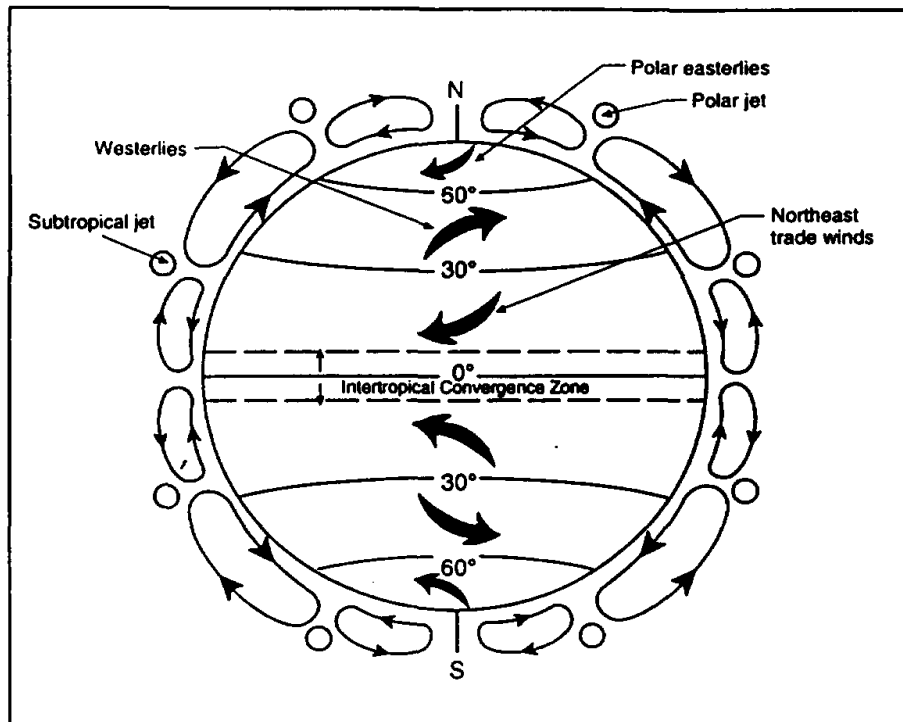


Figure 3-10. General atmospheric circulation cells

Instead of moving toward the equator, some surface air at the 30° latitudes moves toward the poles. The Coriolis force deflects these winds to the east in both hemispheres. These surface winds blow from west to east and are called the **prevailing westerlies** or **westerlies** in both hemispheres. Between 30 to 60° latitudes, traveling pressure systems and associated air masses (discussed later) help transport energy. Moist air from southerly regions are transported northerly. This moisture condenses, liberating energy that helps heat the air in the northerly latitudes.

In the areas between the 60° latitudes and the poles, the **polar easterlies** prevail. This easterly wind forms a zone of cold air that blows to the southwest (Northern Hemisphere) and to the northwest (Southern Hemisphere) until it encounters the warmer westerly winds. The interface between the polar easterlies and the westerlies is the **polar front** that moves as these two air masses push back and forth against each other. The polar front travels from west to east helping to move cold air southward and warm, moist air northward (N. Hemisphere), thereby bringing heat energy toward the polar regions. As warm, moist air characteristics of the westerlies push up and over the cold, drier easterlies, **stormy weather** develops. Therefore, clouds and precipitation typically accompany the polar front.

As shown in Figure 3-10, narrow bands of high speed winds, referred to as **jet streams**, develop where horizontal temperature differences are great. Although the jet stream varies in size and strength it is generally found between 7.6 and 12.2 km (25,000 and 40,000 ft) above the earth and has speeds typically between 129 and 193 km (80 and 120 mph) depending upon latitude and season. These high altitude winds affect surface winds as they help "steer" surface weather systems. Although the jet stream generally runs east-west