GENERAL CIRCULATION

Local fire-weather elements-wind, temperature, moisture, and stability-respond continually to the varying patterns of pressure systems and to the changing properties of huge masses of air moving in generally predictable circulations over the earth's surface. These broadscale circulations determine the regional patterns of rapidly changing fire weather-long term trends resulting in periods of wetness or drought and above or below-normal temperatures, and in seasonal changes in fire weather. If we are to become acquainted with these variations in fire weather, we must understand how they are brought about, and the settings in which they take place.

The response to overall airflow applies also to local fuel conditions, so an understanding of general air circulation within the troposphere is essential to a usable knowledge of wildland fire behavior.

GENERAL CIRCULATION

So far we have been concerned principally with the static properties of the atmosphere-its temperature, moisture, and pressure. In this chapter we will begin a more detailed consideration of the dynamics of the atmosphere-its motion-which was introduced in chapter 1.

We learned in chapter 1 that the atmosphere is a gaseous mantle encasing the earth held there by gravity-and rotating with the earth. Within this huge envelope of air there are motions of a variable nature. If forces were not present to act on the atmosphere and upset its equilibrium, there would be no atmospheric motion-no circulation. The pressure exerted by the weight of the atmosphere would be the same everywhere at a given level. But disturbing forces are present. The earth is not heated uniformly, and the resultant unequal heating of the atmosphere causes compensating air motions, which tend to reduce the horizontal temperature differences.

The actual motions that are developed within the atmosphere are extremely complex and are not yet fully understood. Theories and models, which have been derived, are not wholly accepted because they do not completely account for all of the observed atmospheric motions. Most of the major features of the global circulations are rather well understood. Therefore, future modifications of present-day theories resulting from further research will not seriously affect out understanding of the general circulation as it relates to fire weather.

PRIMARY CIRCULATION

In equatorial regions the earth's surface receives more solar energy from the sun than it radiates back to space, and therefore acts as a heat source for the air in these regions. In polar regions the earth's surface radiates more energy into space than it receives from the sun. Since equatorial regions do not get hotter and hotter, and since polar regions do not become progressively colder, **there must be some net transport of heat energy from equatorial to polar regions.** Just how this is accomplished is one of the major features of the general circulation that is not completely understood. This transport could be accomplished by closed horizontal "cells" with north-south flow, by large-scale eddies, or, perhaps, by both methods. We will consider both methods.
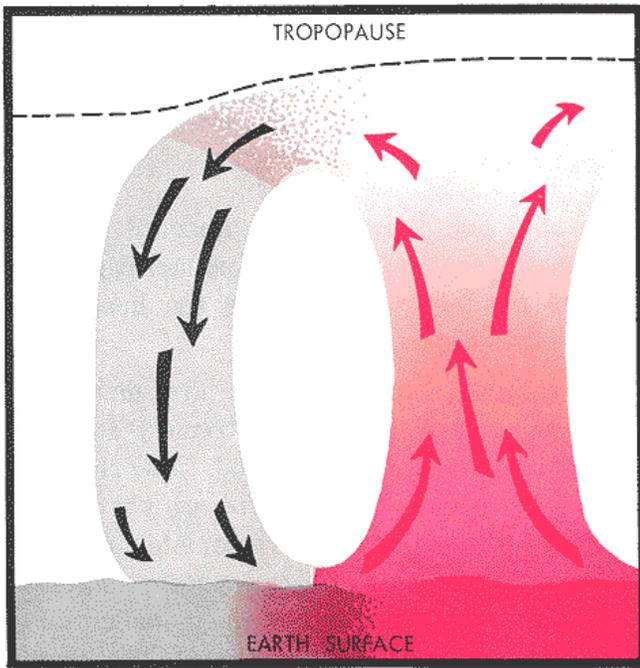
Convective Circulation

Let us suppose that the earth's surface was uniform, that the earth did not rotate, and that it was uniformly heated around the entire Equator.

Certainly this is a very hypothetical situation, but let us accept it for the sake of development of our discussion. We know that regions of warm surfaces, which warm the air overlying them, are characterized by rising air. The warming air expands and is forced aloft by the cooler, denser air flowing in from adjacent areas.

In equatorial regions the warm air would rise to near the tropopause, reach a level of the same air density, then spread out and flow both north and south. As it moved toward the poles, it would cool by radiation and sink as its density increased. In the polar regions it would descend and begin to move toward the Equator.

In this hypothetical case the transport of heat could take place by simple convective circulation. At the earth's surface there would be a permanent low-pressure belt around the earth at the Equator and a high-pressure area at each pole.

In a simple convective circulation, worm air expands and is forced aloft. As it cools, it descends and eturns to the heat source.
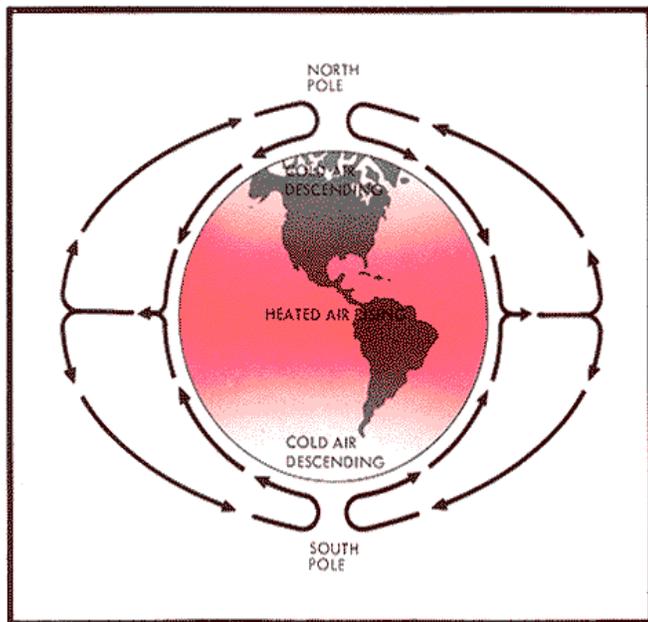
Since the earth does rotate, and since the sun is its single source of energy, this simple convective pattern cannot exist. The real circulation patterns are the result of the unequal

If the general circulation could be represented by a simple convective circulation, heated air at the Equator would rise to near the tropopause, then spread out both north and south. Toward the poles, it would cool, and finally descend and move back to the Equator.

heating mentioned above combined with the effect of the earth's rotation and the unequal partitioning of heat due to the uneven distribution of land and sea areas. Before we discuss the circulation on a rotating earth with a uniform surface, we will need to consider why and how the earth's rotation affects airflow.

## How the Earth's Rotation Affects Airflow: Coriolis Force

If a maps of air, or any other body, moves in a straight line as viewed from a position in space, its path as viewed from a position on the earth is curved. The curvature indicates a deflection to the right in the Northern Hemisphere and a deflection to the left in the Southern Hemisphere. The reason for the deflection is that the earth, rotating toward the east on its axis, turns underneath the moving air or body. This deflective force is called the Coriolis force. It is an apparent rather than a real force, but since we are stationed on earth and view motions from the earth, the deflection is real from all earthbound positions.

To visualize the Coriolis force, let us consider a large disk or merry-go-round, rotating in a counterclockwise direction, as representing the Northern Hemisphere. A boy tossing a ball from the center outward would find that the ball made a straight path in space, but traced a curved path on the disk below showing a deflection toward the right. Although more difficult to visualize, it is a fact that if the boy were stationed at any place on the rotating disk and tossed the ball in any horizontal direction, the ball would trace a curved path on the disk with a deflection to the right.

On the rotating earth, an air current in the Northern Hemisphere starting as a southerly wind, that is, moving toward the north, would be deflected to the right and become a southwest or west wind. Likewise, a north wind deflected to the right becomes a northeast or east wind. Since the northward airflow aloft just north of the equatorial region becomes nearly a true westerly flow, the northward movement is slowed and the air "piles up" at about latitude 30°N. The air also loses considerable heat by radiation.
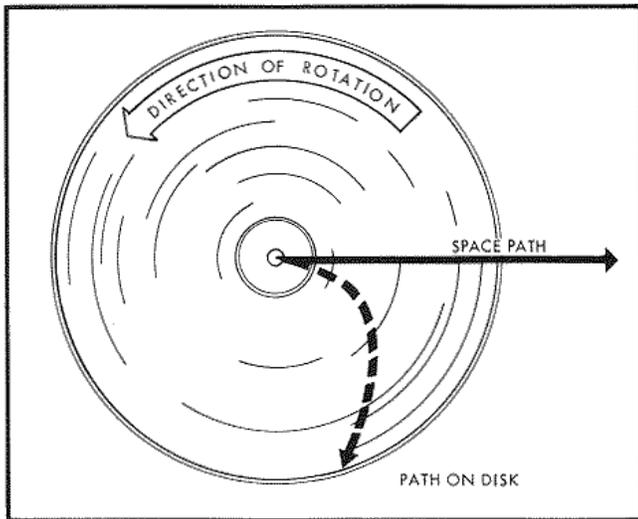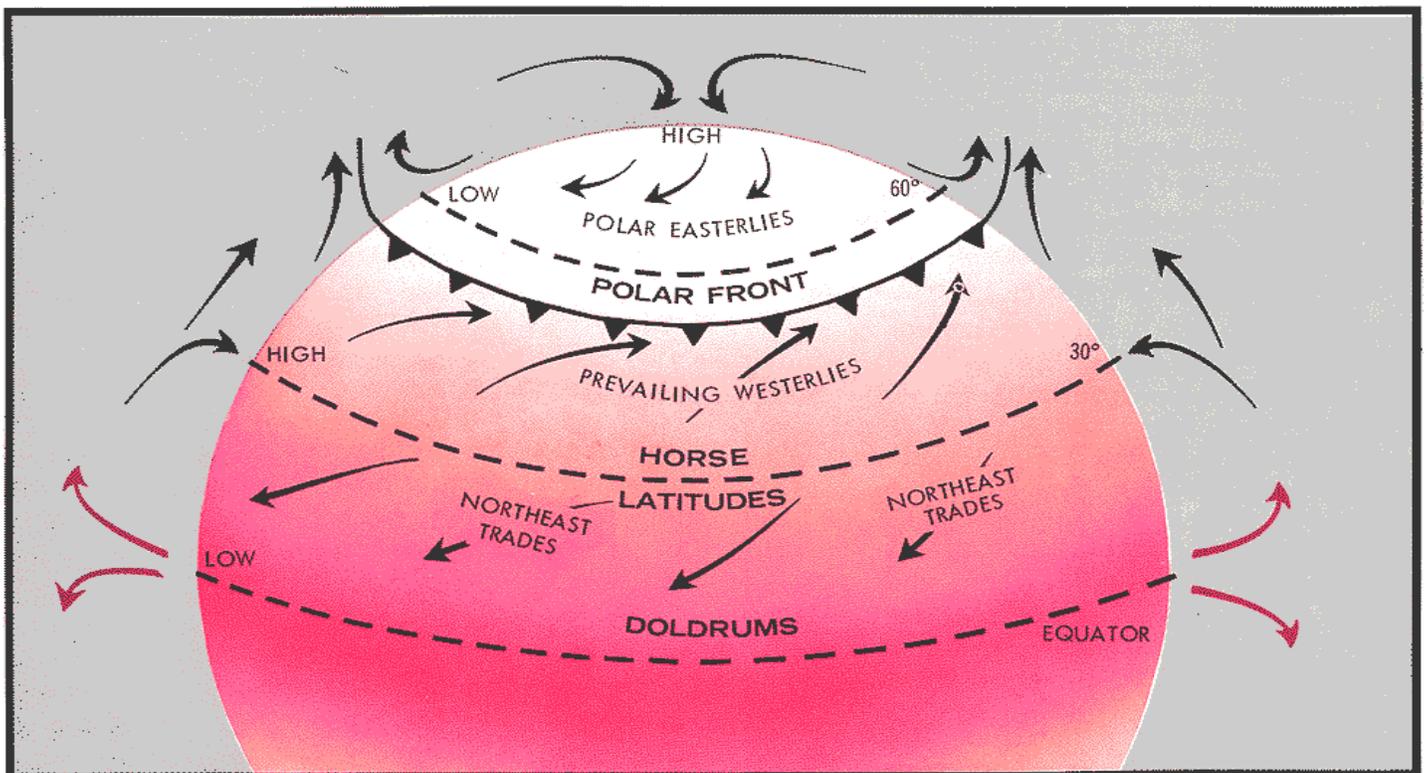
A ball tossed horizontally from the center (or, in fact any location) on a large, counterclockwise rotating disk will take a straight path in space, but, because of the Coriolis force, the path traced on the disk will show a deflection to the right.

of the earth's rotation comes into play. The northward-flowing current is turned to the right and becomes the prevailing westerlies of middle latitudes. The southward-flowing current, also deflected to the right, becomes the **northeast trades of the low** latitudes.

The air aloft that gradually moves northward continue to lose heat. In the polar regions it descends, gives up additional heat to the surface, and flows southward. This current is also turned to the right by the Coriolis force and becomes the polar easterlies of high latitudes. The cold air gradually pushes southward and finally meets the northward-flowing tropical air in what is referred to as the polar front zone. The polar and tropical air masses, which have different densities, tend to resist mixing. Instead, the lighter tropical air flows up and over the forward edge of the denser polar air.

Because of the piling up and the heat loss, some of the air descends, producing a surface high-pressure belt, while the rest continues in the westerly current aloft. Air that has descended flows both northward toward the pole and southward toward the Equator at the surface. Again, the effect

This type of cellular circulation causes air to accumulate in the polar region. When the

On a rotating earth with a uniform surface, the general circulation of the Northern Hemisphere would be composed of the trade winds, prevailing westerlies, and polar easterlies.

mass becomes great enough, the polar front zone is pushed southward, and the cold polar air penetrates to fairly low latitudes in a "polar outbreak". In this simplified circulation system, heat energy is carried northward by the airflow aloft, and cold air moves southward in cold outbreaks to maintain a balance of energy between equatorial and polar regions.

This primary circulation system results in the formation of several well-defined major regional circulation patterns or **wind belts,** some of which we have already mentioned. These are known as: Doldrums, trade winds, horse latitudes, prevailing westerlies, polar front zone, and polar easterlies.

The equatorial region of warm and moist rising air currents is referred to as the **doldrums**. It is a region of light surface winds, considerable cloudiness, and widespread shower activity. When the doldrum belt moves north from the Equator, as it does in the summer and early fall, it becomes the "breeding ground" for tropical storms and hurricanes.

Near latitude 30°N. is a region of descending air and high pressures known m the horse latitudes. As we will see later, the high atmospheric pressure in this region is usually best developed over the oceans. The high-pressure areas are characterized by light variable winds, little cloudiness, and little rainfall. Between the doldrums and the horse latitudes is the belt of trade winds-northeast trades in the Northern Hemisphere and southeast trades in the Southern Hemisphere.
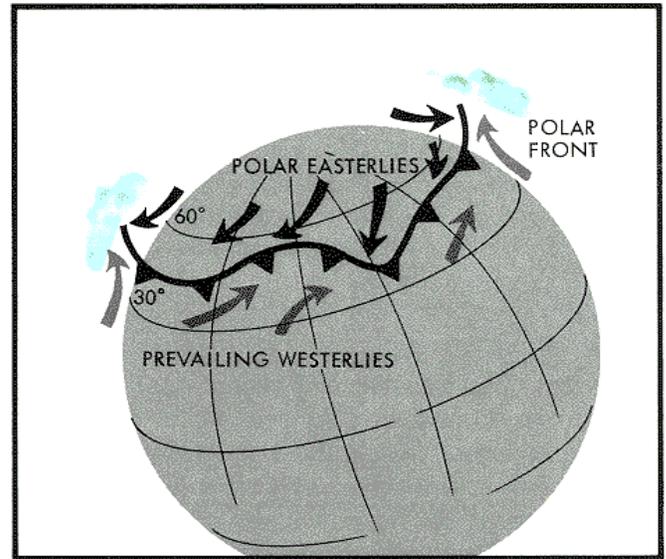
The polar front zone is an area of storminess, cloudiness, and precipitation, and its position is extremely variable.

The belt of westerlies extends from about 30°N. to about 55°N. North of here are the polar easterlies mentioned earlier. The **polar front zone**, between the prevailing westerlies and polar easterlies, is a zone of storminess, doudiness, and precipitation. Its position around the hemisphere is extremely variable. Sometimes it plunges far southward into middle latitudes with cold air outbreaks; at other times it is carried far northward with intrusions of tropical air to high latitudes. We will see later that it is tied to the circulation aloft, particularly to the meandering stream of westerly winds in the upper troposphere.

PRESSURE PATTERNS

The simple primary circulation described above should result in a band of low pressure around the earth in the equatorial region, a band of high pressure about latitude 30°N., a band of low pressure in the polar front zone, and an area of high pressure in the polar region. However, if we study the distribution of pressure over the Northern Hemisphere we do not find the bands to be entirely uniform. Instead we find **pressure cells**-areas with higher or lower pressure than the surrounding region. Some of these are semi permanent cells, which remain relatively fixed; others are migratory.

The weather is closely related to these pressure cells and other pressure patterns. If we are to understand and predict the weather, we need to determine the **distribution of atmospheric pressure.**

Atmospheric pressure was introduced to us in chapter 1. We learned that the atmosphere has mass and that atmospheric pressure is the result of the force of gravity acting on this mass. Atmospheric pressure can be measured by balancing the weight of the atmosphere against that of a column of mercury. This is done with a mercurial barometer. Another type
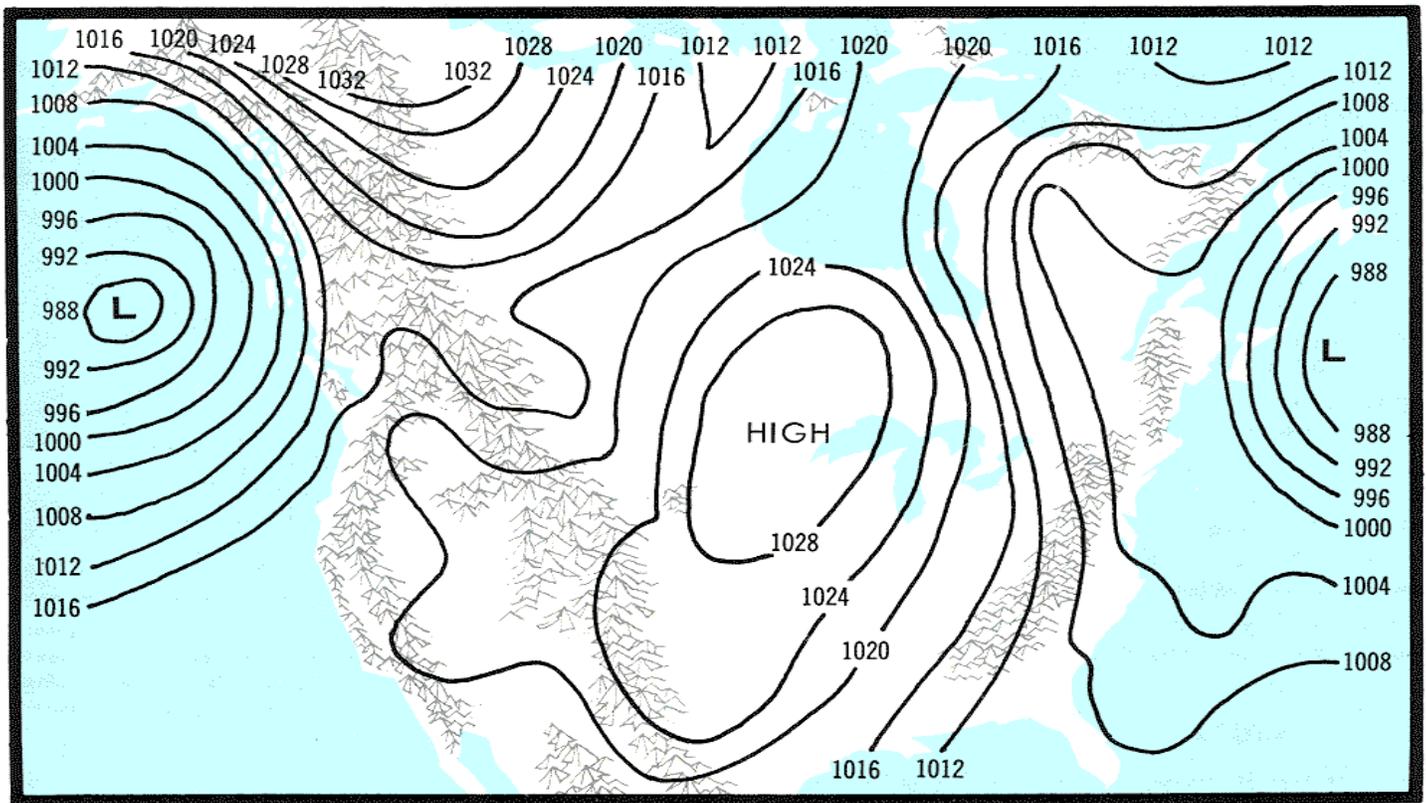
A surface weather map is a graphical picture of the pressure distribution obtained by drawing lines, called isobars, through points of equal sea-level pressure. Isobars outline areas of high and low pressure.

of barometer, called an aneroid, has a partially vacuated metallic cell, so constructed that the sides tend to collapse under increasing atmospheric pressure and to expand with decreasing pressure. This movement is magnified by levers and is transmitted to a hand or pen, which indicates the pressure reading on a scale. We also learned in chapter I that atmospheric pressure at any location varies with time and decreases with altitude.

Constant-Level, Constant-Pressure Charts

To study the pressure distribution, we need, first of all, pressure measurements taken simultaneously at a number of stations. Meteorologists refer to these as synoptic observations. Secondly, since stations are at different elevations and we wish to compare one pressure measurement with another, we need to correct the pressures to a common level, usually sea level. This is done by adding to the station pressure the weight of a hypothetical column

of air extending from the level of the station down to sea level. Corrected readings are collected at a central point and plotted on a weather map. **Such weather maps are called synoptic charts.**

A graphical picture of the pressure distribution is obtained by drawing lines, called isobars, through points of equal pressure. Isobars are labeled in millibars (mb.) and are drawn usually for intervals of 4 mb., although the interval may vary with the map scale. Isobars may be thought of as contours of pressure, somewhat similar to contours of elevations on a topographic map.

Pressure patterns aloft are also important in determining the structure of the atmosphere. They are portrayed in a slightly different way, however. Instead of determining pressure variations at a constant level, such as is done on the sea-level chart just described, the variations in the height of a **constant-pressure** surface are charted. The pressure surfaces used in the

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troposphere are 850 Tabs. (about 5,000 feet), 700 mb. (about 10,000 feet), 500 mb. (about 18,000 feet), and 300 mb. (about 30,000 feet).

The heights above sea level, usually in tens of meters, of the pressure surface at a number of stations are plotted on a weather map. Contours of height for 60-meter intervals are drawn through points of equal height. These contours are strictly analogous to the contours on a topographic map. The only difference is that the constant pressure chart depicts the height of a pressure surface, while the topographic map depicts the height of the ground surface above sea level.

For our purpose, it makes little difference whether we think of pressure distribution in terms of a constant-level or constant-pressure chart. Areas of high pressure on a constant level chart would appear as areas of high heights on a constant-pressure chart, and low-pressure areas would show up as low heights.

Lows, Troughs

When a weather map is analyzed as described above, we find certain configurations, or
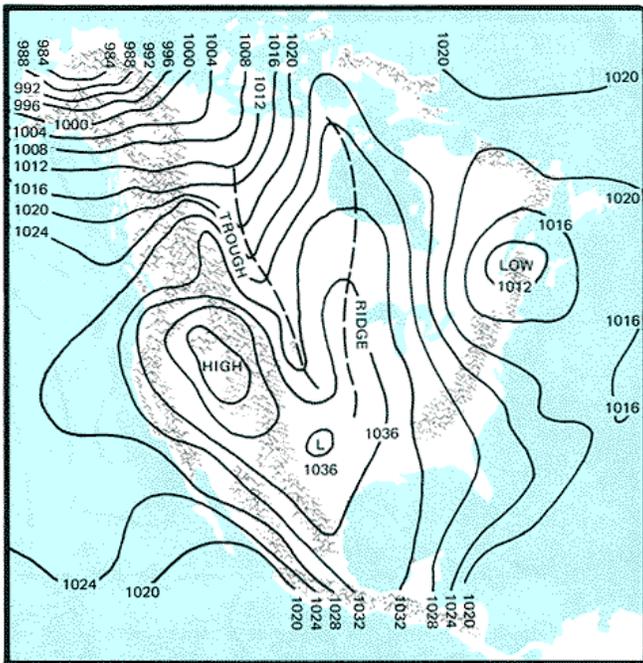
Air around a low flows counterclockwise in the northern Hemisphere and spirals inward. This converging airflow produces rising motion, and, if sufficient moisture is present, precipitation will result.
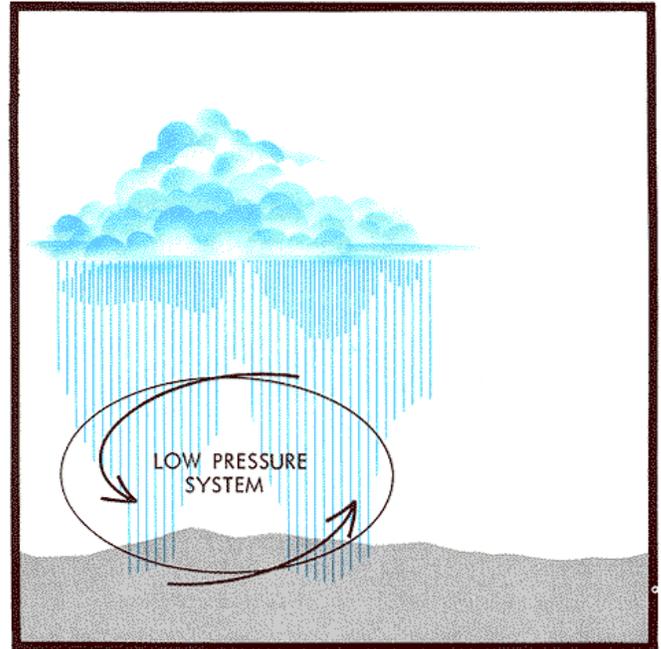
A line of low pressure is referred to as a trough, and a line of high pressure is referred to as a ridge. The curvature of the isobars in a trough is cyclonic; in a ridge, anticyclonic.

patterns. On a sea-level chart we will find areas that have a lower pressure than the surrounding region. These are called **low-pressure centers** or areas, or simply Lows for short. They are also called cyclones because the air flows around them in a cyclonic direction (counterclockwise in the Northern Hemisphere). Lows are usually characterized by inward and rising air motion, which results in cooling and increased relative humidity. Sufficient lifting with adequate moisture will produce condensation of water vapor into clouds and may result in precipitation. Latent energy released by the condensation adds to the energy of the circulation system.

A line of low pressure is referred to as a **trough.** The pressure along the line is lower than the pressure on either side. The isobars show a cyclonic curvature at the trough line but do not form a closed circulation. The characteristics of a trough are similar to those of a Low. Frequently a trough delineates the boundary between two different airflows and is a common place for the development of storm centers.
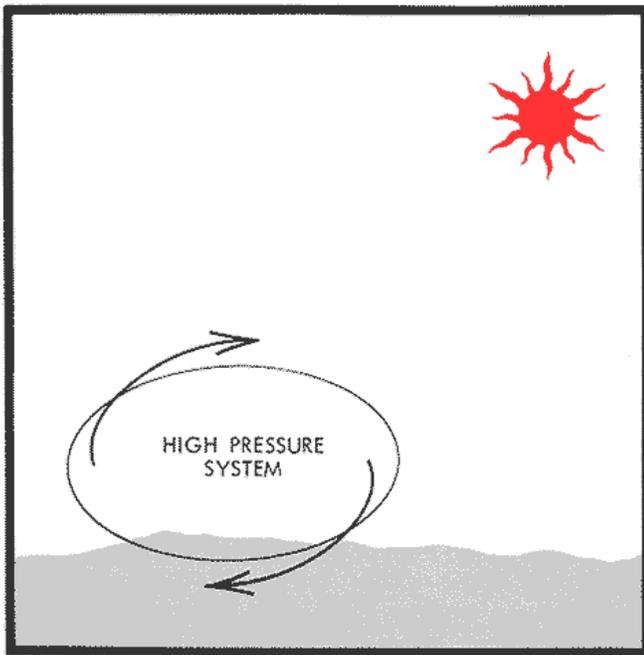
Circulation around a High is clockwise in the Northern Hemisphere and spirals outward. This divergent flow is accompanied by downward motion, with the result that cloudiness and precipitation are minimum/

Highs, Ridges

High-pressure cells are another type of pressure pattern observed on analyzed weather maps. A **high-pressure area** is surrounded on all sides by lower pressure. We call it a **High** for short. It may also be referred to as an anticyclone because the windflaw around a High is anticyclone (clockwise in the Northern Hemisphere). The airflow in a High is generally outward and descending. For this reason, Highs are usually areas of minimum cloudiness and little or no precipitation. If the air descends from very high altitudes, it may be extremely dry.

Ridges are lines of high pressure. The pressure is higher along the ridge than on either side. The curvature of isobars at a ridgeline is anticyclonic, but the isobars do not form a closed circulation. Ridges exhibit characteristics similar to Highs, with descending air and a minimum of cloudiness and precipitation.

PRESSURE AND WIND RELATIONS

Air always moves in response to pressure differences. As it moves, its speed and direction of motion are governed by a combination of forces. These include the pressure-gradient force, which causes air to move from high to low pressure; the **Coriolis force,** which causes a deflection to the right in the Northern Hemisphere; an outwardly directed centrifugal force if air is flowing in a curved path; and friction, which opposes all air movement near the surface of the earth.

Airflow can take place along a straight or curved path. Let us consider first the simpler case, that is, straight flow at a level high enough in the atmosphere so that friction with the earth's surface is negligible. For this case, only two of the forces mentioned above need be considered the pressure-gradient force and the Coriolis force.

Pressure gradient may be defined as the change of pressure per unit distance, for example, millibars per 100 miles. On the sea level map, as mentioned above, isobars are drawn for specific intervals of pressure. The

closer the isobar spacing, the stronger the pressure gradient, and vice versa. The pressure gradient force tends to make air flow across the isobars from high to low pressure. But, as the air moves, it is deflected to the right by the Coriolis force. This force acts in a direction perpendicular to the airflow, and its magnitude depends upon both the speed of the airflow and upon the latitude. The reason for this is that the Coriolis force is caused by the rotation of the earth's surface beneath the airflow, and the rotation of the surface around a vertical axis depends upon the latitude. This rotation, and therefore the latitudinal effect of the Coriolis force, is greatest at the poles and decreases to zero at the Equator.

Geostrophic, Flow

Balance between the pressure-gradient force and the Coriolis force is achieved when these two forces oppose each other with equal magnitudes. The resulting flow is then parallel to the isobars, rather than across the isobars. If these forces are diagrammed, the pressure-gradient
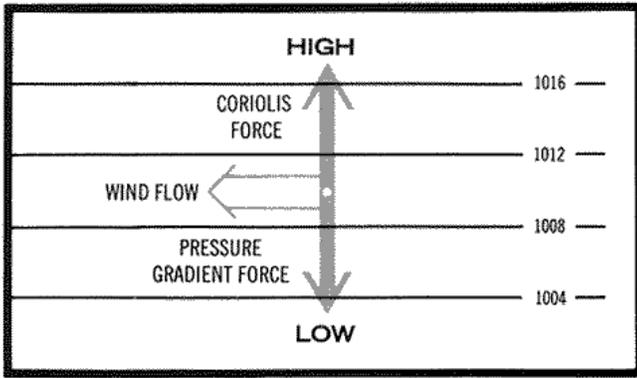
Geostrophic flow occurs in regions of straight-line isobars. The pressure-gradient force from high to low pressure balances the Coriolis force, which is at right angles to the flow. The flow is parallel to the isobars, with high pressure on the right.

force is drawn at right angles to the isobars in the direction of low pressure. The Coriolis force is drawn at right angles to the line of motion and is directed toward the right in the Northern Hemisphere.

At a given latitude the speed of the airflow, increases with an increased pressure gradient - a decrease in the distance between isobars. With equal pressure gradients, a greater air speed will occur at lower latitudes than at higher latitudes because of the influence of latitude on the Coriolis force.

Straight flow, which occurs in regions of straight-line isobars, is termed geostrophic flow and implies balance between the pressure gradient and Coriolis forces.

Gradient Flow: Highs and Lows

In most areas on a weather map the isobars are curved rather than straight. The result is
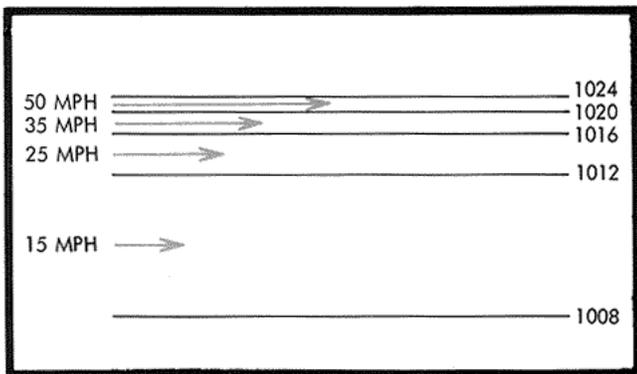
At a given latitude, the speed of the airflow increases with increased pressure gradient; that is, with a decrease in the distance between isobars.

that as air moves, the direction of the pressure gradient force changes, and so does the airflow, to follow the curving isobars. Here, an additional force must be considered-the outwardly directed centrifugal force. For steady motion, a balance must exist between the pressure-gradient force, the Coriolis force, and the centrifugal force. When these forces are in balance, the airflow is still parallel to the isobars, but it is known as gradient flow. As with geostrophic flow, high pressure is on the right in the Northern Hemisphere, as one looks downstream. Therefore, the direction of flow is always clockwise around a high-pressure center and counterclockwise around a Low.

The balance of forces for gradient flow is more complicated than for geostrophic flow. If the forces around a Low were diagrammed, the pressure-gradient force is drawn at right angles to the isobars and directed inward. The Coriolis force is at right angles to the airflow and directed toward the right, which is outward, and the centrifugal force is at right angles to the isobars and directed outward. When the
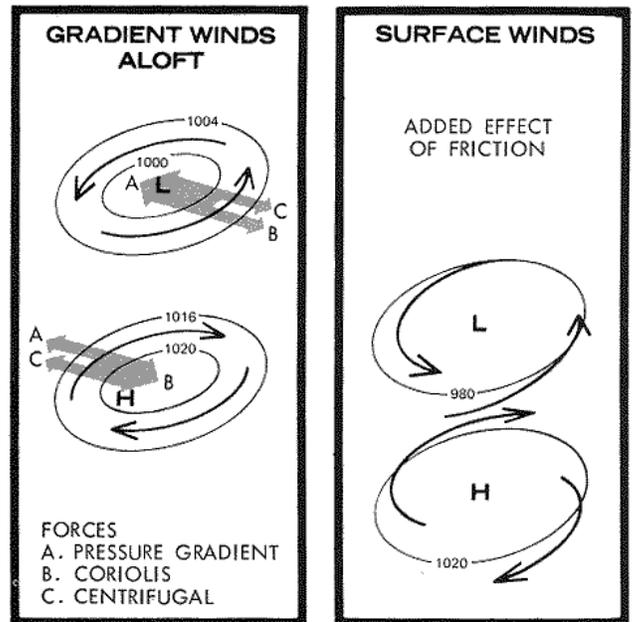
Left. – In a low the pressure-gradient force tends to balance the Coriolis and centrifugal forces, and the resultant flow is cyclonic (counterclockwise in the Northern Hemisphere). In a High the Coriolis force tends to balance the pressure-gradient and centrifugal forces, and the resultant flow is anticyclonic. Right. – Friction with the earth's surface causes air to flow spirally outward across the isobars from a High and spirally inward around a Low.

three forces are in balance; the pressure-gradient force balances the sum of the Coriolis and centrifugal forces.

If the forces around a High are diagrammed, the centrifugal force is, of course, still directed outward. But now the pressure gradient force is directed outward, and the Coriolis force is directed inward. This means that the sum of the pressure-gradient and centrifugal forces balances the Coriolis force.

In both low- and high-pressure systems, the speed of the wind increases with increased pressure gradient; that is, with closer spacing of the isobars. Because the centrifugal force is added to the pressure-gradient force in a High, and subtracted from it in a Low, the wind speed in a High will be greater than in a Low with the same pressure gradient. In spite of this, we find higher wind speeds in Lows because the pressure gradients are usually much stronger.

One other characteristic difference also exists. In a low-pressure system, increased pressure gradients and increased air speeds may occur as the center is approached. We can have, and of ten do observe, very strong wind speeds near the center of Lows. In a High,

however, because of the balance of forces there is a limiting value of wind speed that cannot be exceeded as the center is approached. We find, therefore, that Highs have low wind speeds and weak pressure gradients near their centers.

Friction

So far we have considered straight flow and curved flow at levels high enough in the atmosphere so that the force of friction could be disregarded. But when we consider airflow near the ground, we must account for the friction force. The effect of friction on airflow is to retard the movement. Therefore, friction is a force acting in a direction opposite to the airflow. Since the Coriolis force varies with the wind speed, a reduction in the wind speed because of friction produces a reduction in the Coriolis force.

For steady motion there must be a balance among the pressure-gradient, centrifugal, Coriolis, and friction forces. The resulting balanced motion is a flow directed slightly across the isobars from high to low pressure. The amount of deviation depends upon the roughness of the terrain and will vary from 10 to 15 degrees over water to 25 to 45 degrees over
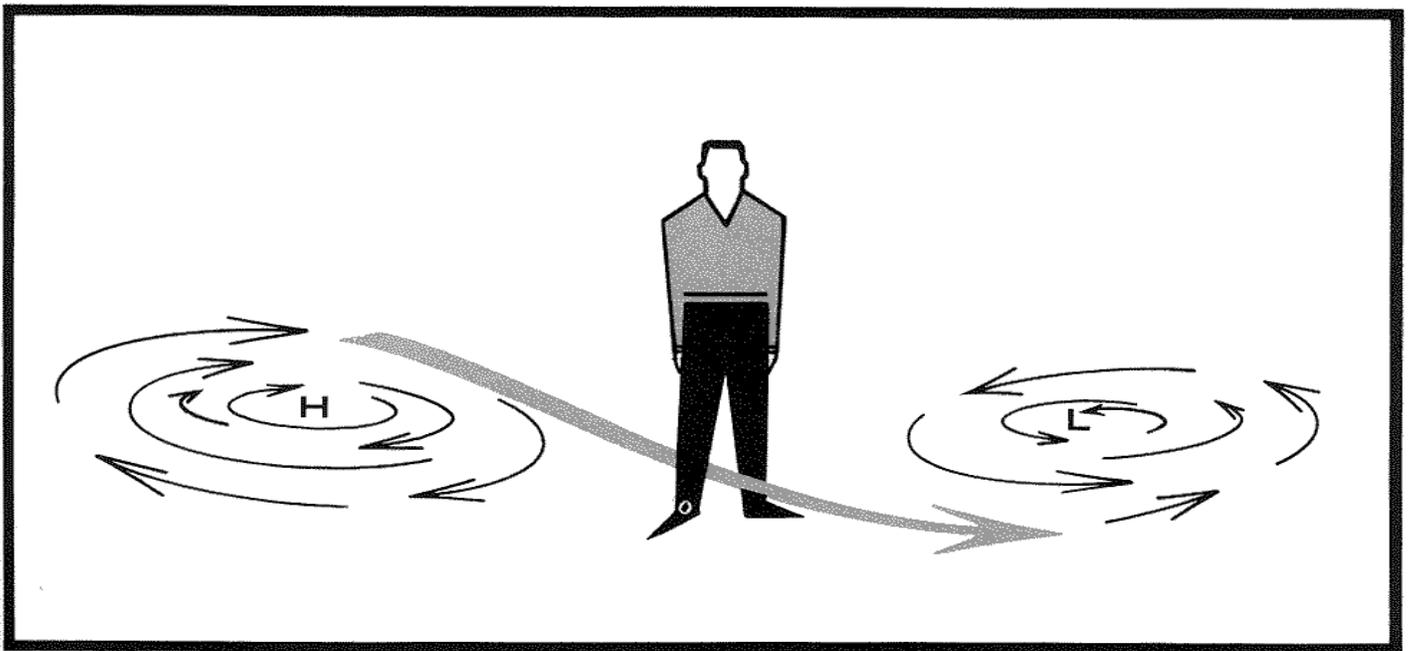
"Back to the wind, high pressure on the right" is a useful rule. Because of friction, air near the surface flows from high- to low-pressure areas. Air accumulated near the surface in low centers is forced aloft; the removal of air from High centers requires downward displacement of air.

land. The speed of the airflow is always lower with friction than without friction.

Friction assists in the transfer of air from high- to low-pressure areas. Because of friction, air flows spirally outward from a High and spirally inward around a Low near the surface. A person standing with his back to the wind has high pressure to his right and a little to the rear, and low-pressure on his left and a little forward. The effect of friction is, of course, greatest near the surface and decreases upward in the atmosphere. The depth of its influence varies directly with surface roughness and with atmospheric instability.

Generally, at altitudes higher than 2,000 feet above the surface, the effect of friction can be disregarded. Above this altitude, the airflow tends to be more nearly parallel to the isobars.

The development of new pressure systems, and the intensification or decay of existing systems, as well as the migrations of these systems, cause many deviations in observed wind speeds and directions. Additional deviations develop because of local terrain. The combined effects of these influences can be seen by comparing the observed surface winds with the sea-level isobars on a surface weather map.

CIRCULATION PATTERNS AT UPPER LEVELS

Our discussion of Highs, Lows, troughs, ridges, and the relationship between pressure and wind has been concerned primarily with the surface map, which is a constant-level map. The same terms and the same relationships apply to constant pressure charts used to portray the upper-air circulations described earlier. The balance of forces for airflow on a constant-pressure chart is similar to that on a constant-level chart. The only difference is that the pressure-gradient force is represented by the gradient of height of the constant-pressure surface. The friction force is disregarded on upper-air charts.

The circulation patterns in the middle and upper troposphere are quite different from those near the surface. They are less complicated because the effects of local heating of land and water, and of topography on air movements are greatly reduced. The major or large-scale hemispheric circulations are more in evidence. Troughs and ridges are common, but completely closed circulations-Highs and Lows-tend to decrease in frequency with altitude.

Circumpolar Westerlies

Except for a deep layer of easterly flow in equatorial regions, which reaches to the upper troposphere, the airflow aloft in the Northern Hemisphere consists of a broad belt of **westerly winds** extending from the subtropics to the polar regions. This belt of westerlies forms a large **circumpolar vortex.** An upper-air chart of the

Northern Hemisphere will show that this is not a smooth circular vortex; instead, it is a meandering current forming waves of varying amplitude and wavelength. These horizontal waves appear as part of the pattern of an upper-air chart.

Meteorologists classify the waves into two categories: **Long waves which** usually number three to seven around the hemisphere, and short waves which are superimposed on the pattern of long waves. The long waves move slowly. They may drift eastward slowly; remain stationary for a number of days, and even retrograde on occasion. The westerly current in a long-wave **ridge** may go far to the north and allow tropical air to be carried to high latitudes. In a long-wave **trough,** the westerlies may go far to the south and allow cold polar air to reach low latitudes.

A persistent long-wave pattern plays, an important role in prolonged periods of abnormal weather. The region beneath a long-wave ridge is likely to experience clear, dry weather with above-normal temperatures. The region beneath a long-wave trough is likely to have cloudy, wet weather with below-normal temperatures.

Two types of long-wave patterns in the belt of westerlies are distinguished. One is a large-amplitude, short-wavelength pattern, called **meridional.** It is effective in carrying tropical air to high latitudes and polar air to low latitudes. The other is a small-amplitude, long-wavelength pattern, called **zonal,** in which

the principal movement of Highs and Lows in mid-latitudes is west to east.

Short waves are smaller, rapidly moving oscillations, which proceed through the long wave pattern. They move northward around long-wave ridges and southward through long wave troughs. The speed of the short waves is usually slower than the wind speed aloft, indicating that the air moves through the waves. The short waves are associated with migratory Lows and Highs at the surface, and their movement is about the same speed as the surface systems.

Long waves cannot be shown by lines because the exact positions are usually obscured by short waves. Generally, what one sees are
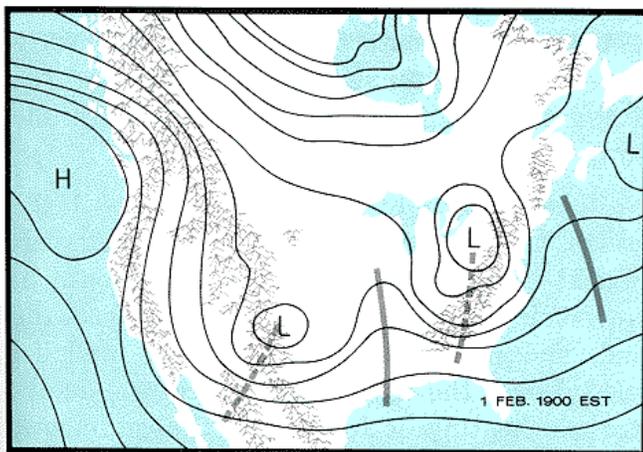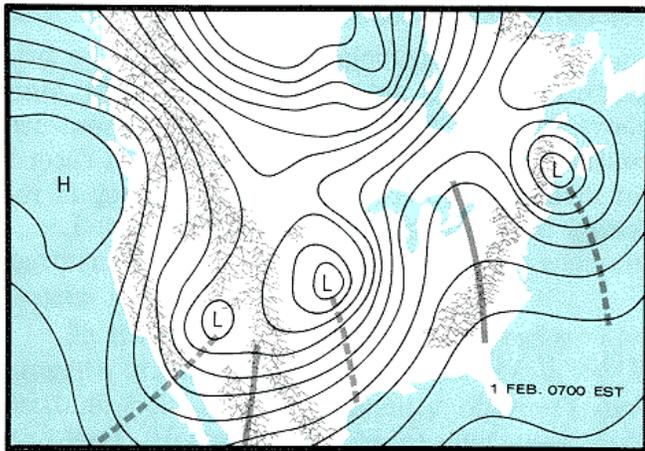
These two 500 mb. charts, 12 hours apart, illustrate short wave moving through the long-wave pattern. Short waves are indistinct in the long-wave ridge position in the Gulf of Alaska. Short-wave troughs, shown by dashed lines, tend to deepen in the long-wave trough position, which extends into Northern Mexico. Short-wave ridges, shown by solid lines, are indistinct in the long-wave trough, but develop as they move out of the trough, as did the one, which moved, from the southwest and Northern Mexico into the Mississippi Valley.

the short-wave troughs and ridges. The long-wave trough positions are usually identified by the place where short-wave troughs deepen. The same applies to long-wave ridge positions and short-wave ridges.

The migration of large-scale eddies - the Highs and Lows - is **the second method of transporting** excess heat away from lower latitudes (mentioned at the beginning of this chapter). The cyclonically rotating Lows in their travel from lower to higher latitudes on the east side of long-wave troughs are effective in pulling warm tropical air far north ahead of them and cold polar air far south behind them. The Lows eventually dissipate at high latitudes. Cold polar Highs moving south, usually on the west side of long-wave troughs, eventually merge with semi-permanent Highs in the horse latitudes. Thus, these large cyclonic and anticyclonic eddies are mechanisms by which warm air is transported northward and cold air is transported southward across the middle-latitude belt of westerlies.

Closed circulations are sometimes found within the troughs and ridges aloft. Contours may indicate a closed High in a large-amplitude, long-wave ridge. Closed Lows may be found in long-wave troughs, and occasionally in short-wave troughs.

Jet Stream

Within the belt of westerlies there is often a core of very strong winds, called a jet stream. This fast-flowing river of air near the tropopause has wind speeds of 50 to 150 or 200 m.p.h. It is usually 100 to 400 miles wide and 3,000 to 7,000 feet deep. When more than one jet stream occurs, the principal one is the polar-front jet stream associated with the surface polar front. It meanders in a wavelike pattern as part of the general westerly flow. Like the polar front, it is stronger in some places than others. It rarely encircles the entire hemisphere as a continuous river of air. More frequently, it is found in segments 1,000 to 3,000 miles long.

The north-south temperature gradient in the upper troposphere is concentrated in the jet-stream region. In fact, the jet stream is found only in those areas where a marked temperature gradient has developed. Below the
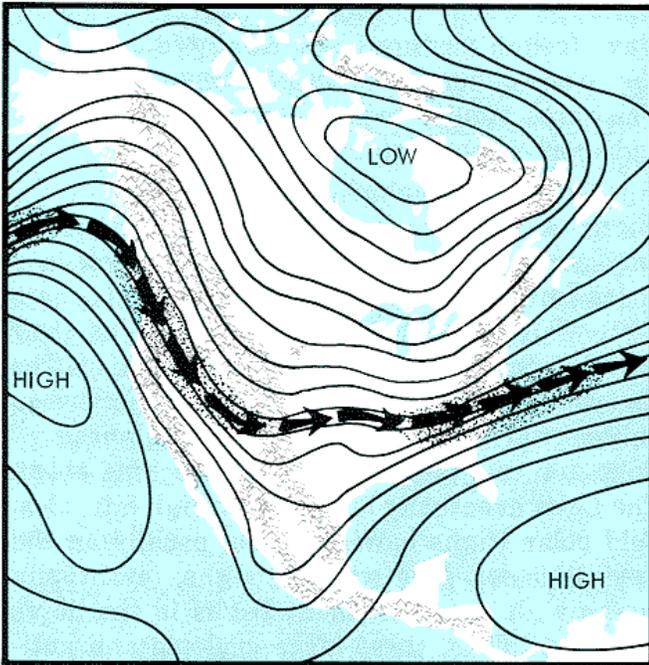
The jet stream, as shown on a constant-pressure chart in the upper troposphere, is meandering, fast-flowing river of air embedded in the belt of westerlies. The stippling shows the regions of strongest winds that move along the jet stream.

jet, the region to the right is warm as one faces downstream, and the region to the left is cold. Above the jet stream, the warm and cold regions are reversed.

The mean position of the jet stream, and the belt of westerlies in which it is embedded, shifts south in the winter and north in the summer with the seasonal migration of the polar front. As it moves southward in the winter it also moves to higher altitudes and, on the average, its speed increases. The seasonal position of the jet stream is related to seasonal weather. During some summers its mean position may not be as far north as usual, and this position reflects summers that are cooler than normal. Similarly, during winters that are milder than normal, the jet stream does not move as far south as usual.

Although the polar jet stream is the primary one, other jet streams may exist high above surface fronts where the temperature contrast between air masses is sharp. A second jet stream south of the polar front jet is referred to as the subtropical jet.

TYPICAL CIRCULATION PATTERNS

The circulations that we observe are the combined results of the primary it secondary circulations, which, in turn, are produced by the uneven heating of the earth because of differences in latitude and in the distribution of land and water masses.

Semi-permanent Centers

As mentioned earlier, the nonuniform character of the earth's surface results in cells of high pressure in the horse latitudes and cells of low pressure in the polar front zone, rather than continuous belts. Some high- and low-pressure systems appear so consistently in certain areas that they are considered semi-permanent and are given names.

Those of interest to us are the **Pacific High** in the Pacific, the **Azores-Bermuda High** in the Atlantic, the **Aleutian Low** in the Northern Pacific, and the **Icelandic Low** in the Northern Atlantic. These may be displaced from their normal positions occasionally, and at times portions;

will break off and become migratory, especially the Lows. Usually though, these semi-permanent centers will remain stationary and quite strong for several days or weeks. The Highs tend to be more persistent than the Lows.

The strength of these cells varies with the season, and the development of other, less per-manent cells is also a function of seasons. In the summer, the oceans are colder than the land, and high-pressure centers are well developed over the oceans. Low pressure, due to stronger heating, is found over the continents. Over Southern Asia a semi-permanent Low develops in summer and a similar Low on a smaller scale is found in our Southwest. During the winter, the continents are colder than the oceans. A seasonal High develops in Siberia, and high pressure is common over North America. The semi-permanent Lows over the warmer oceans are well developed.
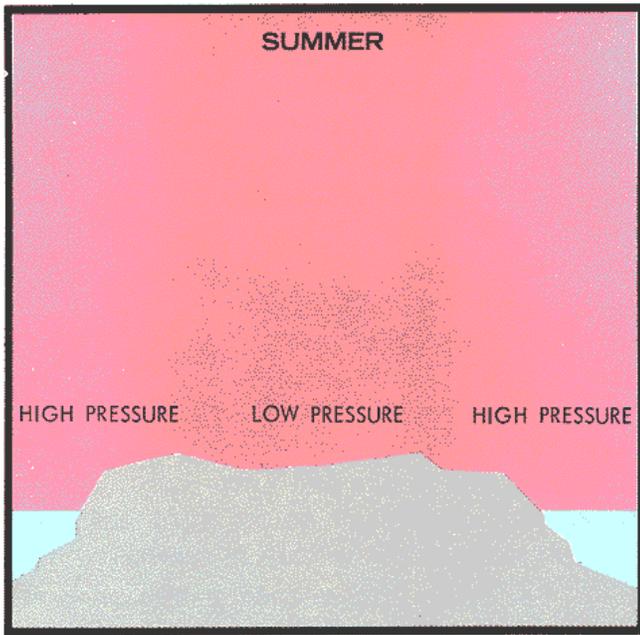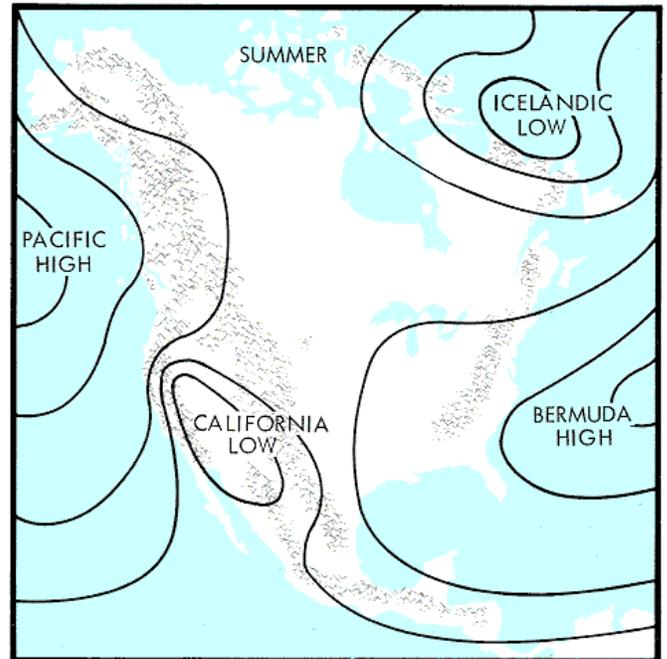
In summer the continents are warmer than the oceans, and there is a tendency for lower pressure over the continents and relatively higher pressure over the adjacent oceans.
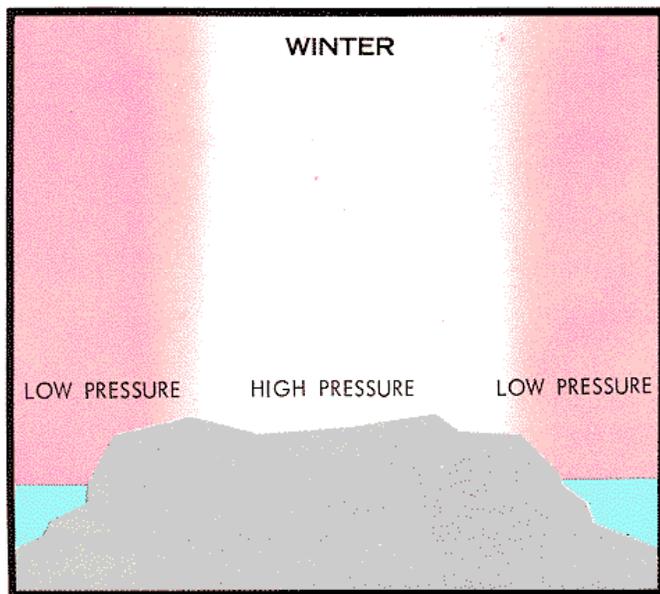
Let us consider the summer and winter patterns over North America and the adjacent means in more detail.

In the summer, because of the comparative warmth of the land, high pressure in the horse latitude belt is not frequently observed over the land. However, the Azores-Bermuda High

In the winter the continents are colder than the oceans, and there is tendency for the denser, stagnating air to form high-pressure cells over the continents while lower pressure exists over the oceans.

often extends into the Southeastern States. The Pacific High and the Azores-Bermuda High are strong and rather far north as compared to their winter positions. The Icelandic Low is weak. The Aleutian Low is not present in the Aleutian area, but low pressure is found over Northeastern Siberia. The intense summer heat over the dry Southwest forms a low-pressure area known as the **California Heat Low.** Temperature contrasts between equatorial and polar regions are smaller in summer than in winter. Pressure gradients are weak, and the resulting air motion is slow compared to winter.


The average July sea-level pressure pattern, representing the summer months, shows the Pacific and Bermuda Highs as being strong and rather far north. The Icelandic Low is weak, pressure is generally low over the continent, and the intense heat in the Southwest forms the California Heat Low.

Aloft, the circumpolar vortex is small. This means that the belt of westerlies, the jet stream, and the polar front are far north. The westerlies an weak and confined to a relatively narrow band. The tracks of most surface Lows are also rather far north; these Lows usually travel eastward through Southern Canada or the Northern States. A few travel northeastward through the Southern and Eastern States or along the Atlantic coast. The tracks of polar Highs me similarly far north.

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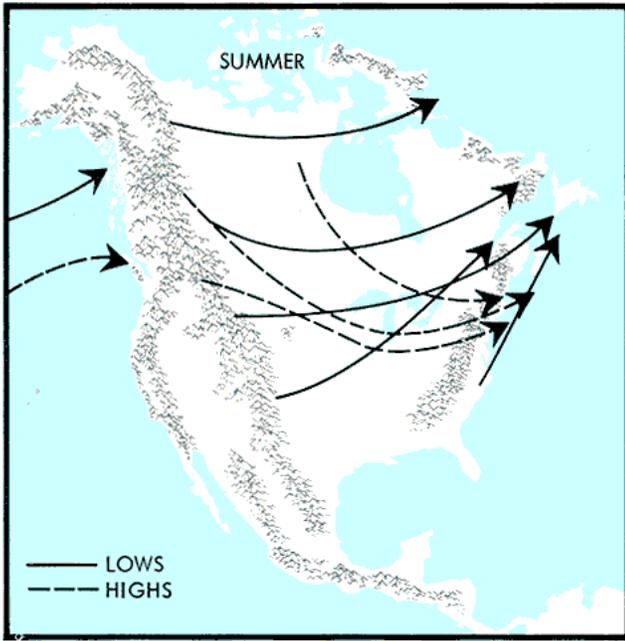
In the summer the preferred tracks of migratory Lows and Highs are rather for north, mostly across Southern Canada or the Northern States. A few Lows travel northeastward along the Atlantic coast.

The strong Azores-Bermuda High and Pacific High have a pronounced influence on summer weather in certain regions. The circulation around the western and of the Azores - Bermuda High (Bermuda High for short) brings warm, moist tropical air from the Atlantic and Gulf of Mexico into most of the Eastern and Central United States. When this High extends far westward across the Gulf States, moisture from the Gulf is effectively cut off, and the East has hot, dry weather.

Along the Pacific coast, the Pacific High blocks most Lows and forces them far to the north. The eastern end of the Pacific High is a region of subsiding air aloft. This subsiding air, which overlays a shallow layer of cool, moist air carried to the mast by northwest winds, produces a very stable condition and results in dry summer weather along the coast.

During winter, the Aleutian and Icelandic Lows are well developed. The Aleutian Low extends from the Aleutian Islands into the Gulf of Alaska, and much stormy weather and precipitation in the Western States are associated with the movement of this low-pressure system or segments of the main cell which break off and move south and southeast. The strong circulation

around the Icelandic Low produces northerly winds and frigid weather in the eastern section of the continent. The Pacific and Bermuda Highs are weaker and displaced farther south in winter than in summer. Temperature contrasts between the tropics and polar regions are greater, and the wind circulations, both aloft and at the surface, are correspondingly stronger.

Aloft, the circumpolar vortex is large, extending to much lower latitudes. The belt of westerlies is broad. The mean position of the polar front is farther south than in the summer. The tracks of Highs and Lows vary considerably, but many take tracks that are much farther south in winter than in summer.

Due to the intense cooling of land areas, particularly at higher latitudes, many cold high-pressure mass develop over the northern half of the continent. Periodically, these high-pres. sure cells move southward, bringing polar or arctic air to the rest of the continent. Stormy weather is produced where these cold outbreaks meet warm, moist tropical air. The coldest Highs in North America come from the Hudson
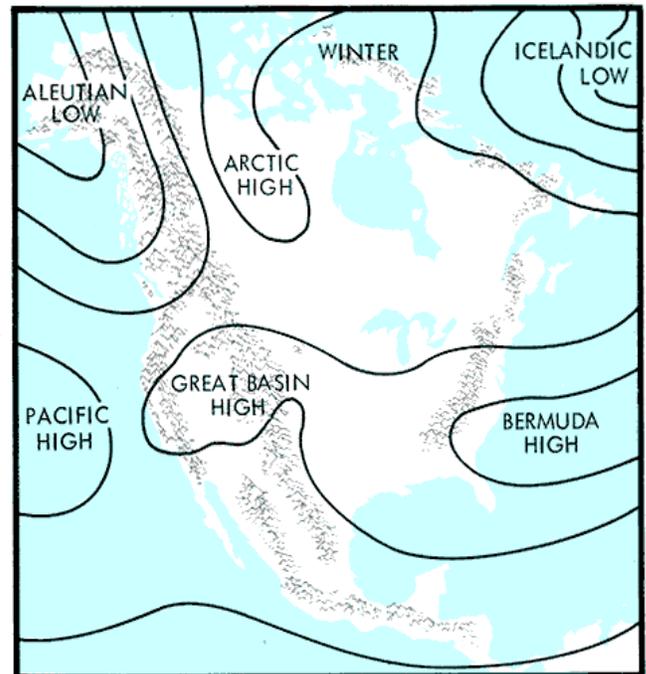
The average January sea-level pressure pattern, representing the winter pattern, shows that the Aleutian and Icelandic Lows are well developed. The Pacific and Bermuda Highs are weaker and farther south han in summer. Pressure us generally high over the cold continent, causing seasonal Highs such as the Great Basin High and the artic High to form.

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WINTER

———LOWS
- - - HIGHS

In winter, preferred tracks of migratory Lows and Highs are farther south than in summer. Periodically, a cold high-pressure cell moves southward from the Hudson Bay Region or Northwest Canada. Pacific Highs move eastward across the continent, but often stagnate for a time in the Great basin.

Bay region or Northwest Canada, while milder Highs move in from the Pacific as break off cells from the Pacific High.

Another wintertime feature is the Great Basin High. Cool air masses from either Canada or the Northern Pacific move into the Great Basin and tend to stagnate in this intermountain area. Dry winds, warmed adiabatically as air flows from higher to lower elevations-including the cast winds of Washington and Oregon, north winds in northern California, and Santa Ana winds in southern California are associated with the track and positioning of the Great Basin High.

A migratory low-pressure cell, called the **Colorado Low,** often develops east of the central Rockies in winter. The circulation system of this Low usually intensifies as it moves to the northeast, reaching maximum development in the Great Lakes or St. Lawrence River area. This Low is usually accompanied by strong winds and rain or snow. The passage of the Low is followed by northerly winds and a cold high-pressure area from the north moving into the Great Plains or Great Lakes region.

Lows that reach the west coast from the Pacific Ocean sometimes move intact over the mountains and continue in an easterly direction along a path curved toward the northeast. Frequently, however, the track of the Low is discontinuous. The Low fills on the west side of the mountains, then reforms on the east side and resumes its eastward movement.

SPECIAL CYCLONIC SYSTEMS

Hurricanes, tornadoes, and waterspouts are special forms of low-pressure systems.

Hurricanes cover a vast area and are quite deep. They originate over warm ocean water in the doldrums or in waves in the subtropical easterlies; and produce heavy precipitation and powerful winds. Large amounts of energy are released to feed these systems through the condensation of water vapor. A distinctive feature of these tropical storms is the virtually calm winds and comparatively clear skies at the center, or eye, of the stem. Hurricanes first move toward the west in the easterly flow and later usually turn north and are caught up in the belt of westerlies. They then take on the characteristics of middle-latitude low-pressure systems. They lose intensity rapidly if

they move over land because of the increased friction and the loss of the continuous supply of moisture.

Tornadoes and waterspots are small low-pressure cells in the form of intense spinning vertexes. When they occur, they are associated with severe thunderstorms. Winds near the center of a tornado are commonly 100 to 200 m.p.h. and may exceed 400 m.p.h. The pressure near the center is extremely low. The great destruction of these terrifying storms is due both to the high winds and the explosive effects of a sudden reduction in pressure as the tornado passes. Tornadoes range from 500 to 2,000 feet in diameter and travel over the ground with a speed of 20 to 40 m.p.h. Water-spouts that develop from the cloud downward

are simply tornadoes occurring over the water. waterspouts develop from the water upward, Usually they are not as intense as tornadoes are weak compared to tornadoes, and dissipate occurring over land. Other "fair weather" rapidly when they move inland.

SUMMARY

In this chapter we have considered the broadscale circulation of the atmosphere, which acts as a gigantic heat engine. The atmosphere is heated by the sun-warmed surfaces in the equatorial regions and is cooled by radiation in the polar regions. Heat is transported from the equatorial regions to the polar regions by the primary circulation and by large-scale atmospheric eddies. Cool air moves from polar regions to low latitudes largely in the form of outbreaks of cold polar air.

Secondary circulations develop because of unequal heating of land and water masses, which, in turn, cause the development of high and low-pressure cells in the atmosphere. The pressure gradients thus produced, along with the apparent force due to the earth's rotation and other forces, cause the development of characteristic circulations around Highs and Lows and other pressure patterns.

Some Highs and Lows are semi-permanent features of the pressure distribution over the earth; others are migratory and produce rapid weather changes. The movement of the migratory systems is closely related to the meanderings of the belt of westerly winds aloft and of the jet stream imbedded in it.

With this background information on the primary and secondary circulation, we are now ready to consider smaller, more local wind systems that occur within the framework of the larger circulations.

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