Chapter 6

GENERAL WINDS

The two most important weather, or weather related, elements affecting wildland fire behavior are wind and fuel moisture. Of the two, wind is the most variable and the least predictable. Winds, particularly near the earth's surface, are strongly affected by the shape of the topography and by local heating and cooling. This accounts for much of their variability and is the reason why there is no substitute for an adequate understanding of local wind behavior.

Wind affects wildfire in many ways. It carries away moisture-laden air and hastens the drying of forest fuels. Light winds aid certain firebrands in igniting a fire. Once a fire is started, wind aids combustion by increasing the oxygen supply. It aids fire spread by carrying heat and burning embers to new fuels, and by bending the flames closer to the unburned fuels ahead of the fire. The direction of fire spread is determined mostly by the wind direction. Thus the fire control plan, in the case of wildfire, and the burning plan, in the case of prescribed fire, must be based largely on the expected winds.

GENERAL WINDS

The atmosphere is in continuous motion. In the previous chapter we considered the large scale motions-the primary circulation resulting from the unequal heating of the equatorial and polar regions of the earth, and the secondary circulations around high- and low-pressure areas produced by unequal heating and cooling of land and water masses.

In this chapter and the next we will investigate the local wind-the wind that the man on the ground can measure or feel. Why does it persist or change as it does? Is it related to the general circulation patterns, or is it produced or modified by local influences? We find that local winds may be related to both, and we will discuss them separately.

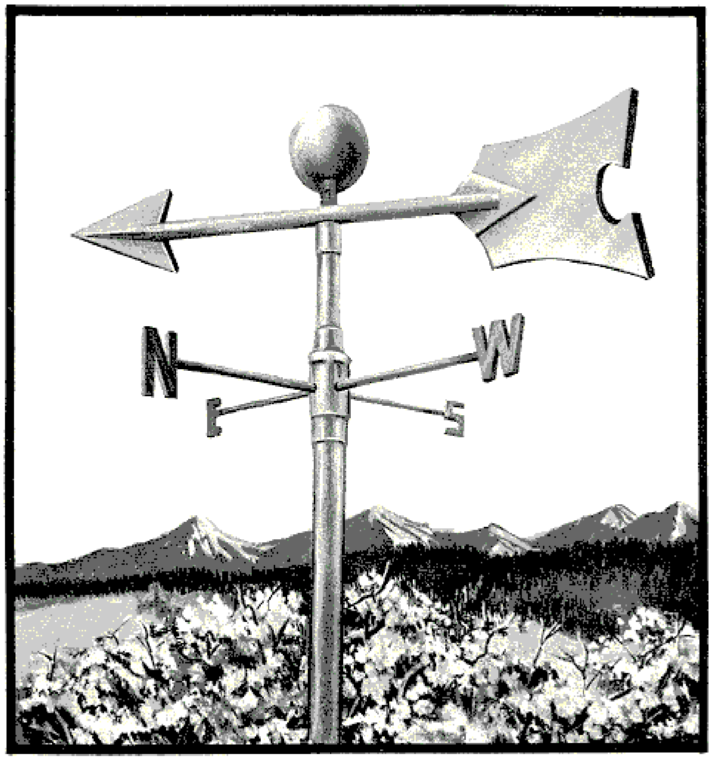
In this chapter we will consider local winds that are produced by the broadscale pressure gradients which are shown on synoptic weather maps, but may be modified considerably by friction or other topographic effects. We will call these general winds. They vary in speed and direction as the synoptic-scale Highs and Lows develop, move, and decay.

In the next chapter, under the heading of convective winds, we will consider local winds produced by local temperature differences. Certainly all winds are produced by pressure gradients, but the distinction here is that the pressure gradients produced by local temperature differences are of such a small scale that they cannot be detected and diagnosed on ordinary synoptic-scale weather charts.

Wind is air in motion relative to the earth's surface. Its principal characteristics are its direction, speed, and gustiness or turbulence. Wind direction and speed are usually measured and expressed quantitatively, while in field practice turbulence is ordinarily expressed in qualitative or relative terms. Ordinarily only the horizontal components of direction and speed are measured and reported, and this is adequate for most purposes. In fire weather, however, we should remember that **winds can also have an appreciable vertical component which will influence fire behavior,** particularly in mountainous topography.

At weather stations making regular weather observations, surface **wind direction** is determined by a wind vane mounted on a mast and pointing into the wind. The direction can be determined visually or, with more elaborate instruments, it can be indicated on a dial or recorded on a chart.

Wind direction is ordinarily expressed as the direction **from which** the wind blows. Thus, a north wind blows from the north toward the south, a northeast wind from the northeast, and so on around the points of the compass. Direction is also described in degrees of azimuth from north-a northeast wind is 45°, a south wind 180°, and a northwest wind 315°.



A wind vane indicates wind direction by pointing into the wind-the direction from which the wind blows.

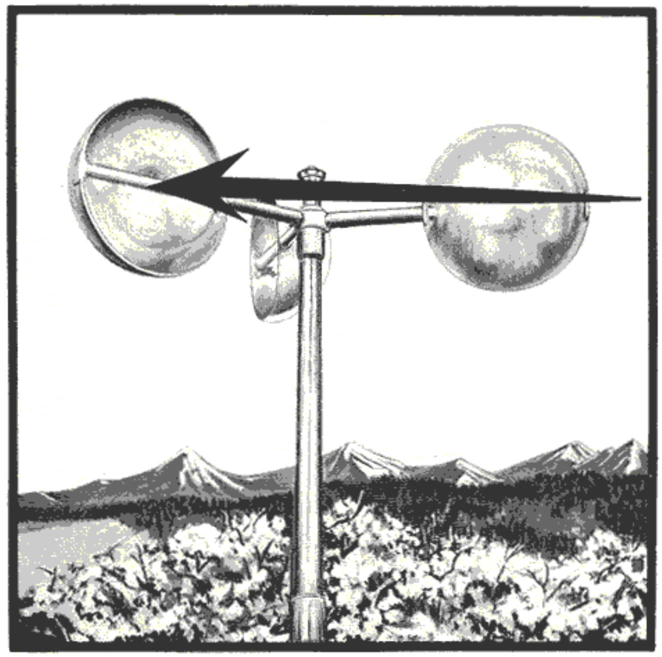
The method of describing the direction of both surface winds and winds aloft, by the direction from which the wind blows, is ordinarily very practical. **In mountain country,** though, surface wind direction with respect to the topography is often more important in fire control and provides a better description of local winds than the compass direction. Here it **is common to express the wind direction** as the direction toward which the wind is headed. Thus, an upslope or upcanyon wind is actually headed up the slope or up the canyon. Wind is described as blowing along the slopes, through the passes, or across the ridges. Similarly, "offshore" or "onshore" are used to describe the directions toward which land and sea breezes are blowing.

Surface wind speeds are measured with **anemometers.** Many types of anemometers are in use, but the most common is the cup anemometer. It indicates either the air speed at any given instant or the miles of air that pass the instrument in a given time period. The latter gives an average wind for the selected time period. Normally, a 2-minute average is used. The standard height at which wind speed is measured is 20 feet above open ground.

In the United States, wind speed is usually measured in miles per hour or knots (nautical miles per hour). One knot is 1.15 miles per hour. Weather Bureau and military weather agencies use knots for both surface and upper winds, while miles per hour is still in common use in many other agencies and operations, including fire weather.

The direction and speed of winds aloft are determined most commonly by tracking an ascending, gas-filled balloon from the surface up through the atmosphere.

The simplest system employs a **pilot balloon** followed visually with a theodolite. If a constant rate of rise of the balloon is assumed, periodic readings of elevation and azimuth angles with the theodolite allow computation of average wind direction and speed between balloon positions. Errors are introduced when the



Horizontal wind speed is measured by the rate of rotation of a cup anemoter.

ascent rate is not constant because of vertical air currents. If a radiosonde unit (which transmits temperature, moisture, and pressure data during ascent) is added to the balloon, the height of the balloon at the time of each reading can be calculated fairly accurately, and the computed winds are more accurate.

The most refined of present systems has the further addition of a self-tracking, radio direction-finding unit that measures elevation and azimuth angles, and slant range from the observing station to the balloon. This unit, known as a **rawinsonde,** yields quite accurate upper-air information. All of these methods furnish wind **soundings** for meteorological use and interpretation.

The speed and direction of upper winds are sampled at regular intervals each day at selected weather stations across the continent. These stations are often more than 100 miles apart. Although winds aloft tend to be more uniform than surface winds, there are exceptions. The wind structure over an area some distance from a sampling station may differ considerably from that indicated by the nearest sounding.

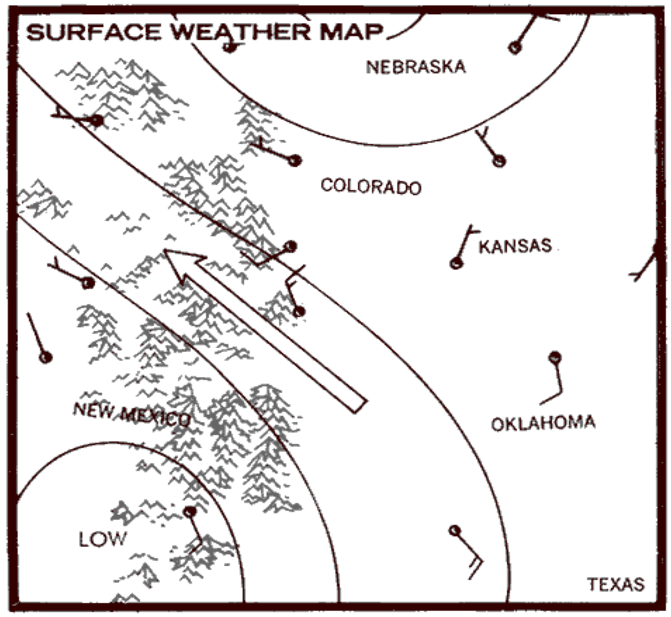
MECHANICAL AND THERMAL TURBULENCE

We learned in the previous chapter that friction with the earth's surface slows down the wind and results in changes of direction so that the surface wind blows at an angle across the isobars from high to low pressure. The amount of reduction in speed and change of direction depends upon the roughness of the earth's surface. It follows then that the effect of friction is least over smooth water and greatest over mountainous topography.

The depth of the air layer through which the frictional force is effective also varies with the roughness of the surface; it is shallower over smooth surfaces and deeper over rough topography. The depth may also vary with the stability of the lower atmosphere. A low inversion will confine the frictional effect to a shallow surface layer, but a deep layer can be affected if the air is relatively unstable. These effects vary widely both with time and between localities.

Usually the friction layer is considered to be about 2,000 feet deep. The top of the friction layer is the gradient wind level above which the windflow tends to parallel the isobars or Pressure-surface contours.

Surface winds often vary considerably in both speed and direction over short intervals of time. They tend to blow in a series of gusts and lulls with the direction fluctuating rapidly. This irregular air motion is known as **turbulence,** which may be either mechanical or thermal in nature. At the surface, turbulence is commonly identified in terms of eddies, whirls, and gusts; aloft it is associated with "bumpy" flying.



The wind direction at surface stations may differ widely from the windflow above the friction layer, as shown by this weather map. Surface wind direction is indicated on weather maps by a wind arrow flying with the wind. The number of barbs on the tail represent the wind speed. At the top of the friction layer the wind blows parallel to the isobars, as shown by the large arrow.

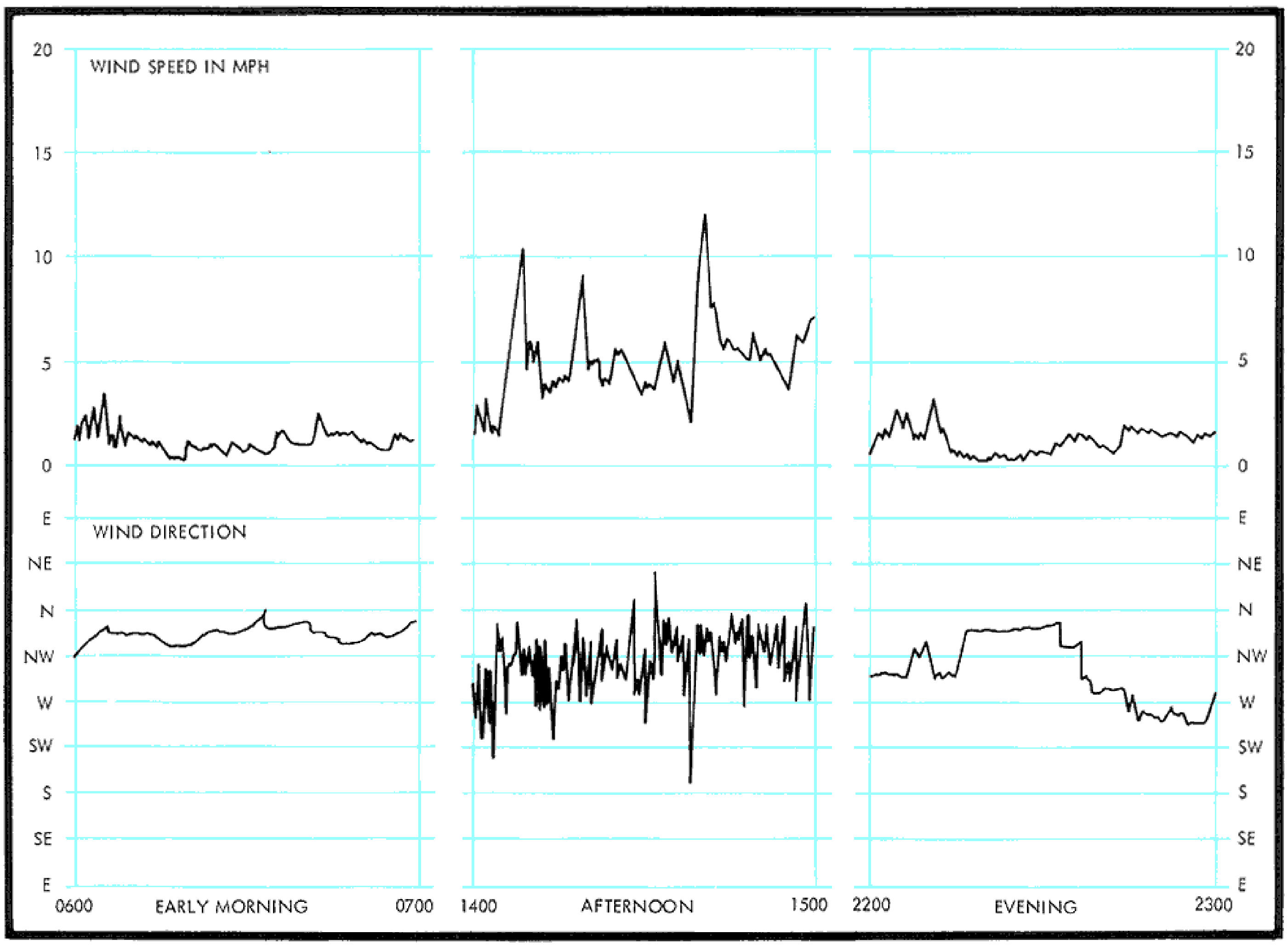
Surf ace friction produces mechanical turbulence in the airflow. The flow of stable air

Roughness creates mechanical turbulence, while surface heating causes thermal turbulence in the airflow.

near the surface is similar to the flow of water in a creekbed. At low speeds the currents of air tend to follow the general contours of the landscape. But when the speed increases-as when a creek rises-the current "tumbles" over and around hills and ridges, structures, trees, and other obstacles, and sets up eddies in all directions. Mechanical turbulence increases with both wind speed and the roughness of the surface.

Thermal turbulence is associated with instability and convective activity. It is similar to mechanical turbulence in its effects on surface winds, but extends higher in the atmosphere. Since it is the result of surface heating, thermal turbulence increases with the intensity of surface heating and the degree of instability indicated by the temperature lapse rate. It therefore shows diurnal changes, and **is most pronounced In the early afternoon** when surface heating is at a maximum and the air is unstable in the lower layers. It is at a minimum during the night and early morning when the air is more stable. Mechanical and thermal turbulence frequently occur together, each magnifying the effects of the other.

Thermal turbulence induced by the combination of convection and horizontal wind is the principal mechanism by which energy is exchanged between the surface and the winds aloft. Unstable air warmed at the surface rises to mix and flow along with the winds above. This turbulent flow also brings air with higher wind speeds-greater momentum-from aloft down to the surface, usually in spurts and gusts. This momentum exchange increases the aver-



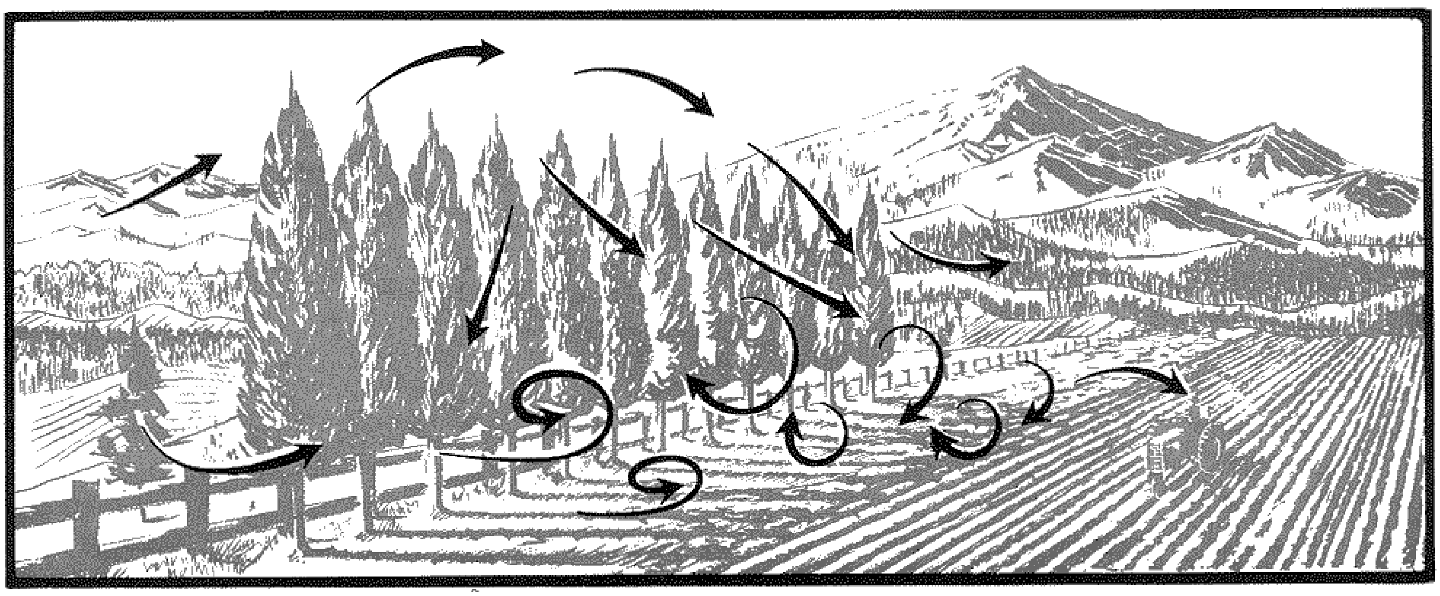
On clear days over flat terrain, thermal turbulence, as indicated by the fluctuations in wind speed and direction, shows diurnal changes because of day heating and night cooling. Turbulence is most pronounced in early afternoon when surface heating is maximum and the lower layers of air are unstable, and least pronounced during the night and early morning when air is stable.

Thermal turbulence caused by surface heating is a mechanism by which energy is exchanged between the surface and he flow aloft. This mixing brings higher wind speeds from aloft down to the surface, usually in spurts and gusts.

age wind speed near the surface and decreases it aloft. It is the reason why surface winds at most places are stronger in **the afternoon than** at night.

Eddy formation is a common characteristic of both mechanical and thermal turbulent flow. Every solid object in the wind path creates eddies on its lee side. The sizes, shapes, and motions of the eddies are determined by the size and shape of the obstacle, the speed and direction of the wind, and the stability of the lower atmosphere. Although eddies may form in the atmosphere with their axes of rotation in virtually any plane, it is usual to distinguish between those which have predominantly vertical or horizontal axes. A whirlwind or dust devil is a vertical eddy, as are eddies produced around the corners of buildings or at the mouths of canyons with steep sides. Large, roughly cylindrical eddies that roll along the surface like tumbleweeds are horizontal eddies.

Eddies associated with individual fixed obstructions tend to remain in a more-or-less stationary position in the lee of the obstruction. If they break off and move downstream, new ones form near the obstruction. The distance



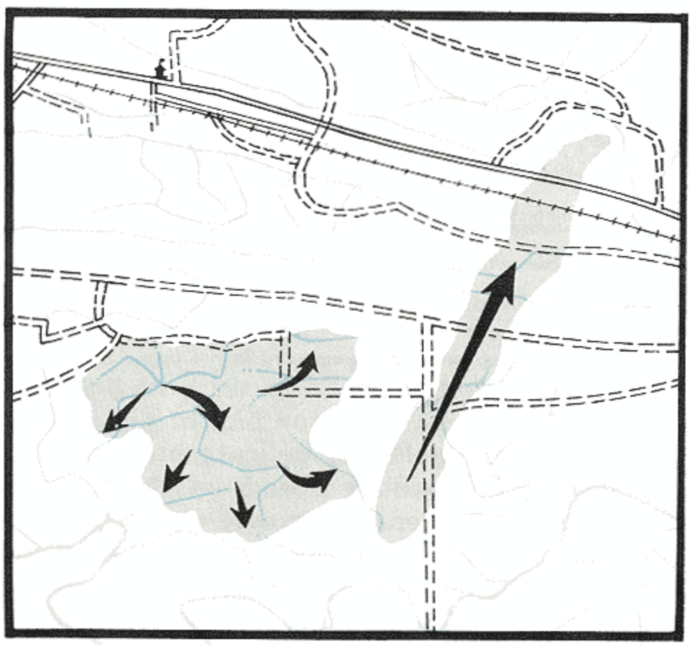
Eddies form as air flows over and around obstacles. They vary with the size and shape of the obstacle, the speed and direction of the wind, and the stability of the lower atmosphere.

downwind that an obstacle, such as a windbreak, affects the windstrearn is variable. For most obstructions, the general rule of thumb is that this distance is 8 to 10 times the height of the obstacle.

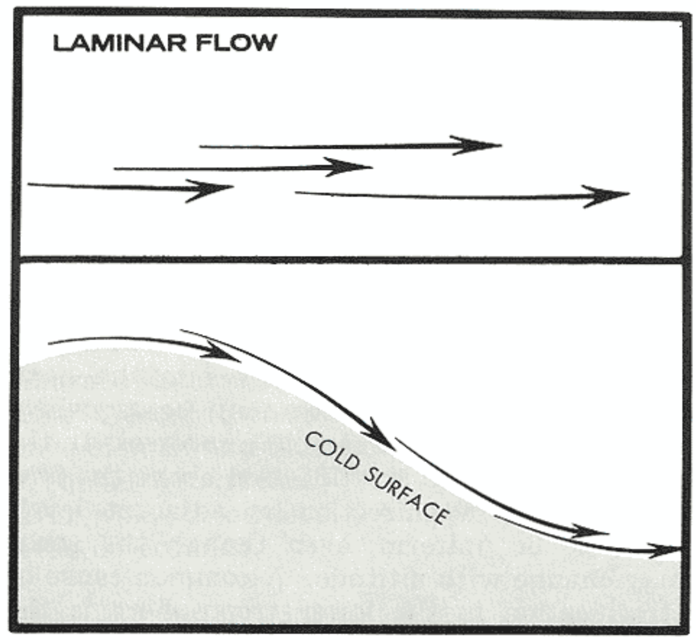
Rotation speeds in eddies are often much greater than the average wind speeds measured with mechanical anemometers. These higher speeds are often of short duration at any point, except where stationary eddies are found, but are still significant in fire behavior. Whirlwinds, for example, develop speeds capable of lifting sizable objects. Eddies moving with the general windflow account for the principal short-term changes in wind speed and direction known as gustiness.

The absence of turbulence-a steady even flow-is called laminar flow. The term suggests air moving along in flat sheets or layers, each successive thin layer sliding over the next. Laminar or near-laminar flow occurs in stable air moving at low speeds. It is characteristic of cold air flowing down an incline, such as we might find in a nighttime inversion. The air flows smoothly along, following the topography and varying little in speed. Vertical mixing is negligible.

True laminar flow is probably rare in wildland fire situations, but, on occasion, turbulence is minor and, for all practical purposes, surface winds do have the steady speed and direction characteristic of laminar motion. While turbulent winds usually cause more erratic fire behavior, the laminar type may result in more rapid and sustained fire spread in one direction. Laminar flow is most likely to occur at night. It is frequently observed over open plains and gently rolling topography.



The nature of the wind during a wildfire is shown by the shape of the burned area. Turbulent winds usually cause more erratic fire behavior and firespread in many directions, while laminar flow is likely to result in spread in one direction.



In laminar flow there is little mixing. The air flows smoothly along, one layer seeming to slide over the next. Laminar flow is characteristic of cold air flowing down an incline.

WINDS AILOFT

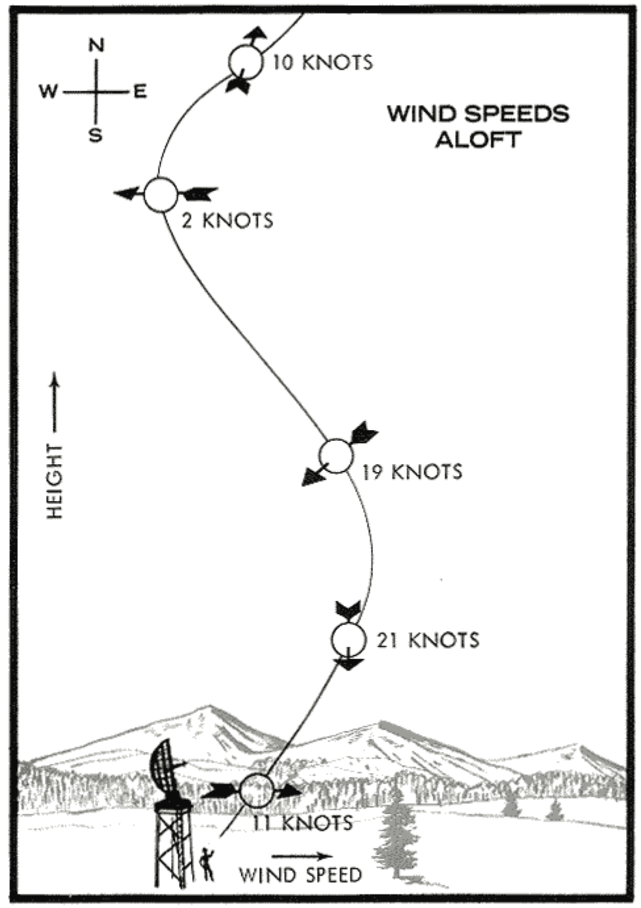
Wildland fires of low intensity may be affected only by the airflow near the surface. But when the rate of combustion increases, the upper airflow becomes important as an influence on fire behavior. Airflow aloft may help or hinder the development of deep convection columns. It may carry burning embers which ignite spot fires some distance from the main fire. The winds aloft may be greatly different in speed and direction from the surface winds.

Usually, we separate winds into **surface winds and winds aloft.** There is no sharp separation between them, but rather a blending of one into the other. We think of surface winds as those winds measured with instruments mounted on surface-borne masts or towers. Winds aloft are those measured with airborne equipment from the surface layer up to the limit of our interest. In ascending from the surface through the lower atmosphere, there is a transition in both speed and direction from the surface to the top of the **friction layer,** which is also called the mixing layer. The depth of this friction or mixing layer is, as we saw when we considered the effects of friction dependent upon the roughness of the terrain and the intensity of heating or cooling at the surface. The winds aloft above the mixing layer are more steady in speed and direction, but they do change as pressure centers move and change in intensity.

Pressure systems higher in the troposphere may differ markedly from those near the surface. At progressively higher altitudes, closed pressure systems are fewer. Furthermore, it is common for the troposphere to be **stratified or layered.** With height, there may be gradual changes in the distribution of Highs and Lows. These changes produce different wind speeds and directions in the separate layers. With strong stratification the wind direction may change abruptly from one layer to the next. The difference in direction may be anywhere from a few degrees to complete reversal. In the absence of marked stratification above the friction layer, wind direction at adjacent levels tends to be uniform, even though the speed may change with altitude. A common cause of stratification in the lower troposphere is the overriding or underrunning of one air mass by another. Thus, the layers often differ in temperature, moisture, or motion, or in any combination of these.

Wind Profiles

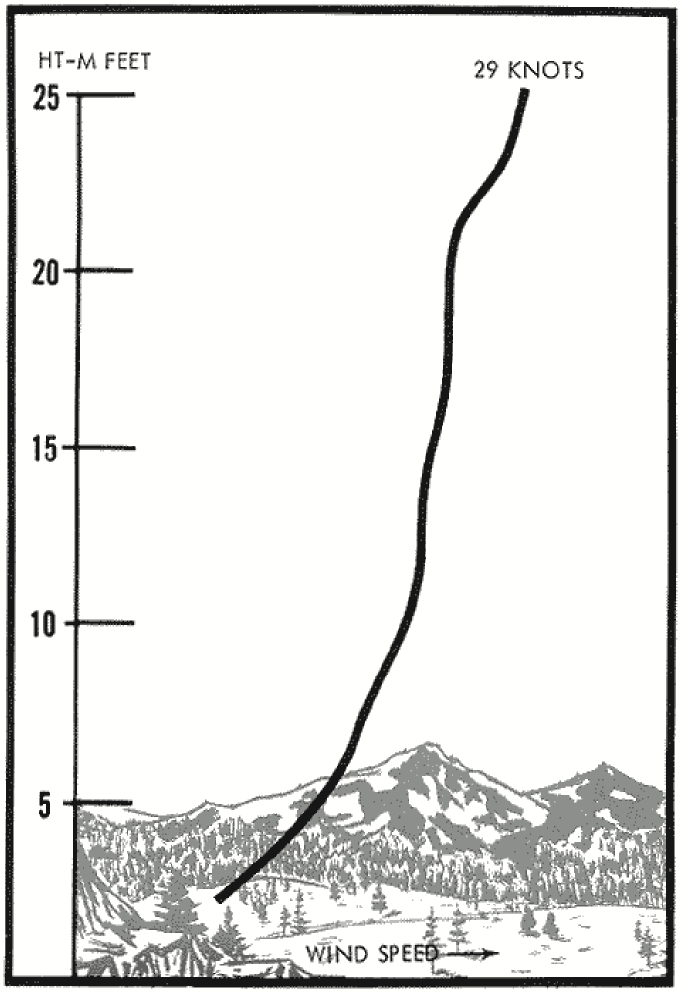
Marked changes in either wind speed or direction between atmospheric layers often occur with an inversion which damps or prevents vertical motion, whether it is convection over a fire or natural circulation in the formation of cumulus clouds. Even though a **wind speed profile-a plot of wind speed** against height-



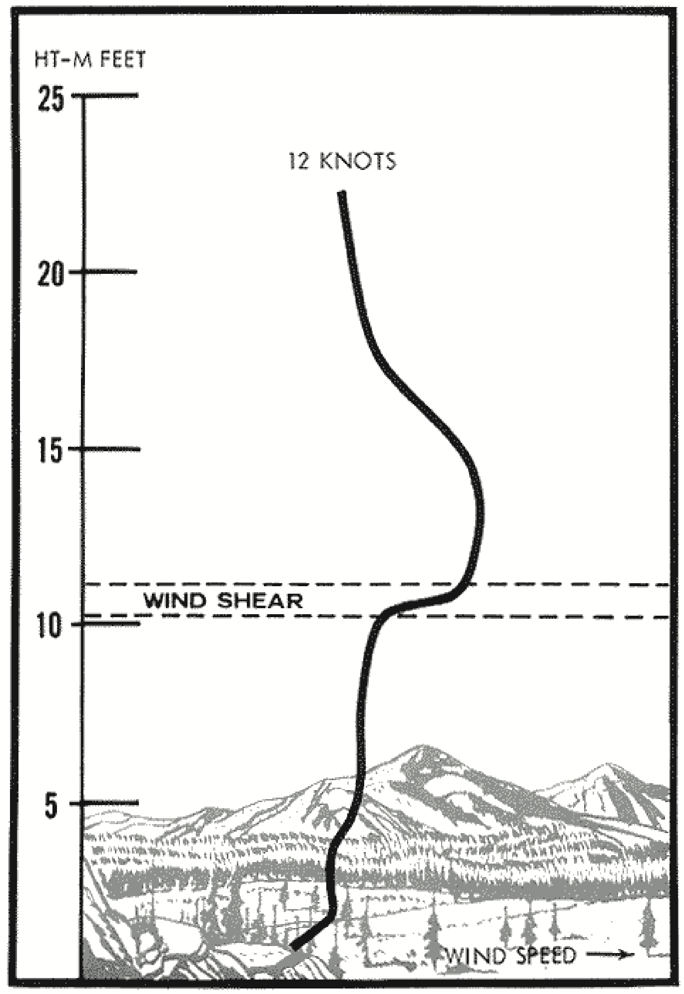
Wind speeds and directions aloft in a stratified atmosphere may vary from one layer to the next. The arrows indicate horizontal directions according to the compass card in the upper left.

of the upper air might indicate only nominal air speeds, the relative speeds of two air currents flowing in nearly opposite directions may produce strong wind shear effects. **Wind shear** in this case is the change of speed or direction with height. Clouds at different levels moving in different directions, tops being blown off growing cumulus clouds, and rising smoke columns that break off sharply and change direction are common indicators of wind shear and disrupted vertical circulation patterns.

Local winds-aloft profiles commonly fall into one or another of several general types. The accompanying illustrations show four types. The soundings were taken on different days at one station and reveal some characteristic differences in winds-aloft patterns. One profile is characteristic of a well-mixed atmosphere without distinct layers. In another, wind shear



A wind profile without abrupt changes in wind speed or direction is characteristic of a well-mixed atmosphere,



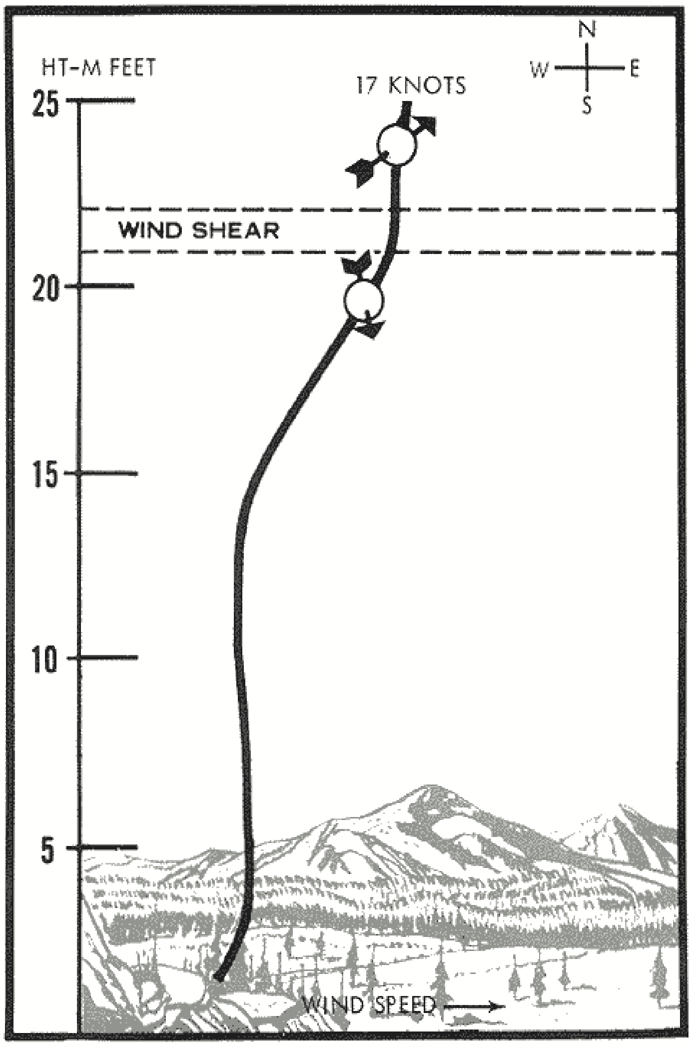
Wind shear occurs where wind speeds change abruptly.

is found in a region of abrupt change in wind speed, and in another wind shear is the result of a sharp change in direction. An interesting feature of the fourth is the occurrence of a **low-level jet** wind near the surface with relatively low wind speeds above.

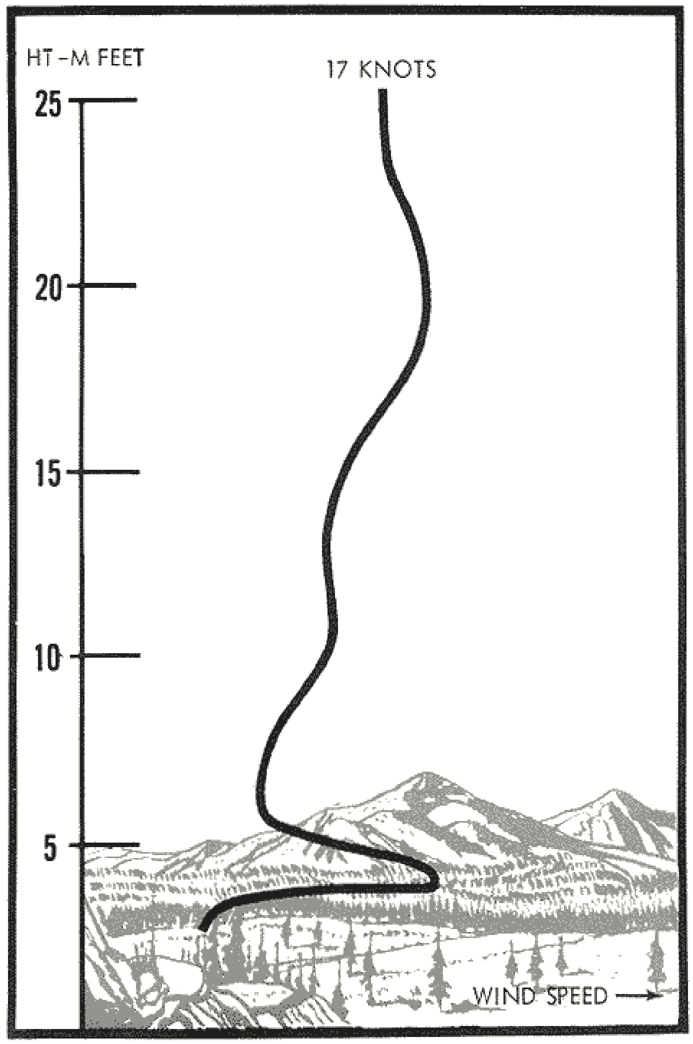
Low-level jets are predominantly Great Plains phenomena although they do occur in other areas. A layered structure of the lower few thousand feet of the atmosphere appears to favor their formation. In fair weather, this strongly suggests a greater probability of occurrence at night than during the day. Stratification in the first few thousand feet is discouraged by daytime heating and thermal mixing, and encouraged by cooling from the surface at night. For example, these jets have been observed to reach maximum speeds in the region just above a night inversion. They have not been studied in rough mountain topography; however, the higher peaks and ridges above lowland night inversions may occasionally be subjected to them. A jet within the marine inversion in the San Francisco Bay area is a frequent occurrence. The geographic extent over which a low-level jet might occur has not been determined.

FRONTAL WINDS

The variability of general surface winds during the spring and fall fire seasons is somewhat greater in eastern portions of the continent than during the summer fire season of the mountainous West. The East experiences more frequent and rapid movement of pressure systems than occur in the West. In the West, the major mountain chains tend both to hinder the movement of Highs and Lows and to lift winds associated with them above much of the topography. Strong summer surface heating also diminishes the surface effects of these changes.



A sharp change in direction also causes wind shear. Shear layers usually indicates that the atmosphere is stratified into layer.



Low-level jets occur predominately in night wind profiles in the Plains, but they may also occur elsewhere. The jet is found most frequently just above the night inversion.

As successive air masses move across the land, the change from one to another at any given point is marked by the passage of a front. A front is the boundary between two air masses of differing temperature and moisture characteristics. The type of front depends upon the movement of the air masses.

Where a cold air mass is replacing a warm air mass, the boundary is called a cold front. Where a warm air mass is replacing a cold air mass, the boundary is called a **warm front.** If a cold front overtakes a warm front, the intervening warm air is lifted from the surface, and the air mass behind the cold front meets the air mass ahead of the warm front. The frontal boundary between these two air masses is then called an **occlusion or occluded front.**

In chapter 8 we will consider in detail the kinds of air masses and fronts, and their associated weather. Here, we are concerned only with the general surface winds that accompany frontal passages.

Fronts are most commonly thought of in association with precipitation and thunderstorms. But occasionally fronts will cause neither. In these instances, the winds accompanying the frontal passage may be particularly significant to fire behavior.

The passage of a front is usually accompanied by a **shift in wind direction.** The reason for this is that fronts lie in troughs of low pressure. We learned in the previous chapter that the isobars in a trough are curved cyclonically in the Northern Hemisphere. This means that as a trough, with its front, passes a particular location the wind direction shifts clockwise. The wind behavior during the frontal passage depends upon the type of front, its speed, the contrast in temperature of the air masses involved, and upon local conditions of surface heating and topography.

East of the Rockies, the surface wind ahead of a warm front usually blows from a southeasterly or southerly direction. With the frontal passage, the wind gradually shifts clockwise. The change in wind direction usually amounts to between 45° and 90°; therefore, after the warm front goes by, the wind commonly blows from the southwest. Steady winds, rather than gusty winds, both before and after the frontal passage are the rule, because the layer of air next to the ground is generally stable. Warm-front passages in the mountainous West are fewer, more erratic, and tend to become diffuse.

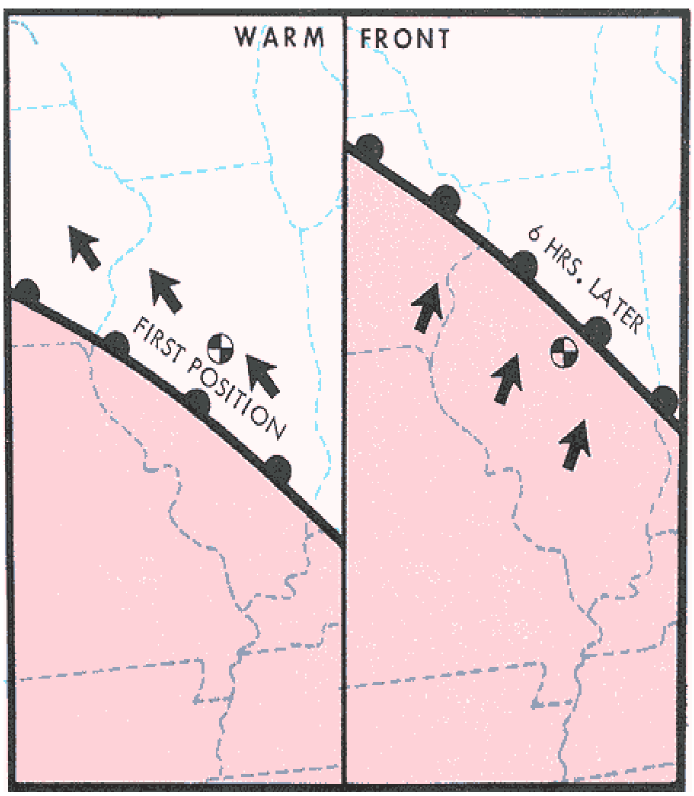
The passage of a cold front differs from that of a warm front. The wind change is usually sharp and distinct, even when the air is so dry that few if any clouds accompany the front. Ahead of a cold front, the surface wind is usually from the south or southwest. As the front approaches, the wind typically increases in speed and often becomes quite gusty. If cold air aloft overruns warm air ahead of the front at the surface, the resulting instability may cause violent turbulence in the frontal zone.

The wind shift with the passage of a cold front is abrupt and may be less than 45° or as much as 180°.

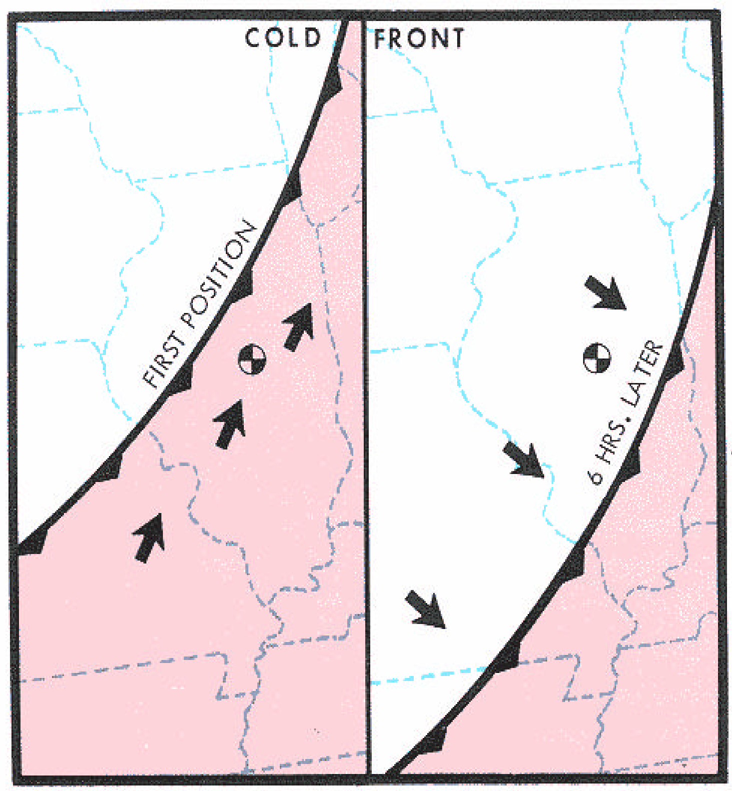
After the front has passed, the wind direction is usually west, northwest, or north. Gustiness may continue for some time after the frontal passage, because the cooler air flowing over warmer ground tends to be unstable. This is particularly true in the spring months. If the temperature contrast is not great, however, the winds soon become steady and relatively gentle.

The wind shift accompanying the passage of an occluded front is usually 90° or more. The wind generally shifts from a southerly direction to a westerly or northwesterly direction as the occlusion passes. The wind shift with an occlusion resembles that of a warm front or cold front, depending upon whether the air behind the occlusion is warmer or colder than the air ahead. The violent turbulence that may accompany a cold-front passage, however, is usually absent with an occluded frontal passage.

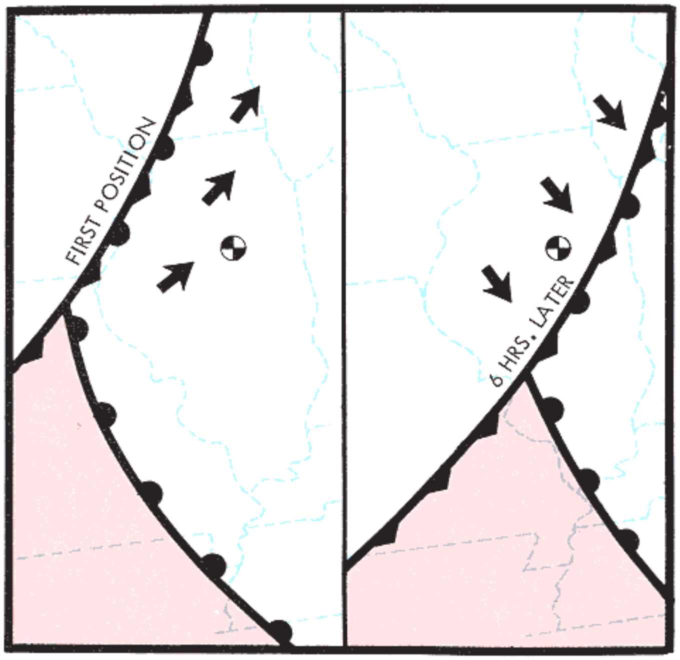
In the area east of the Rockies, squall lines often precede cold fronts. These are narrow zones of instability that usually form ahead of and parallel to the cold front. Most common in



As a warm front passes, wind is steady and shifts gradually, usually from a southeasterly to a southwesterly direction.



Winds increase ahead of a cold front, become gusty and shift abruptly, usually from a southwesterly to a northwesterly direction, as the front passes.

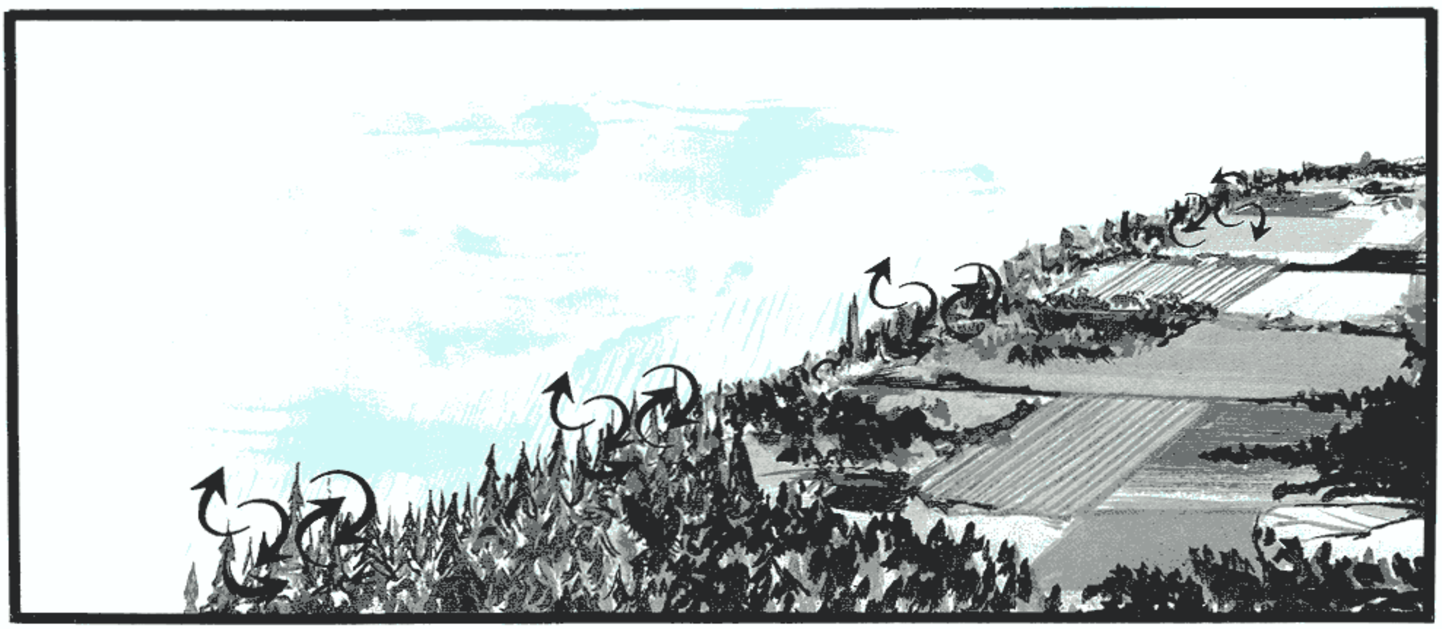


The wind shift accompanying the passage of an occluded front is usually 90° or more, generally from a southerly to a westerly or northwesterly direction.

the spring and summer, squall lines are associated with severe lightning storms in the Midwest and may have extremely violent surface winds. They usually develop quickly in the late afternoon or night, move rapidly, and tend to die out during late night or early morning,

Winds ahead of the squall are usually from a southerly direction. They increase to 30, 40, or even 60 miles per hour, shift to the west or northwest, and become extremely gusty as the squall line passes. The strong, gusty winds ordinarily do not last long, and the winds soon revert to the speed and direction they had prior to the squall. This wind behavior distinguishes a squall line from a cold front.

Squall lines are usually accompanied by thunderstorms and heavy rain. But occasionally the storms are scattered along the line so that any one local area might experience squall-line wind behavior without the fire-quenching benefit of heavy rain.



Squall lines produce violently turbulent winds, usually for a few minutes.

EFFECTS OF MOUNTAIN TOPOGRAPHY

Mountains represent the maximum degree of surface roughness and thus provide the greatest friction to the general surface airflow.

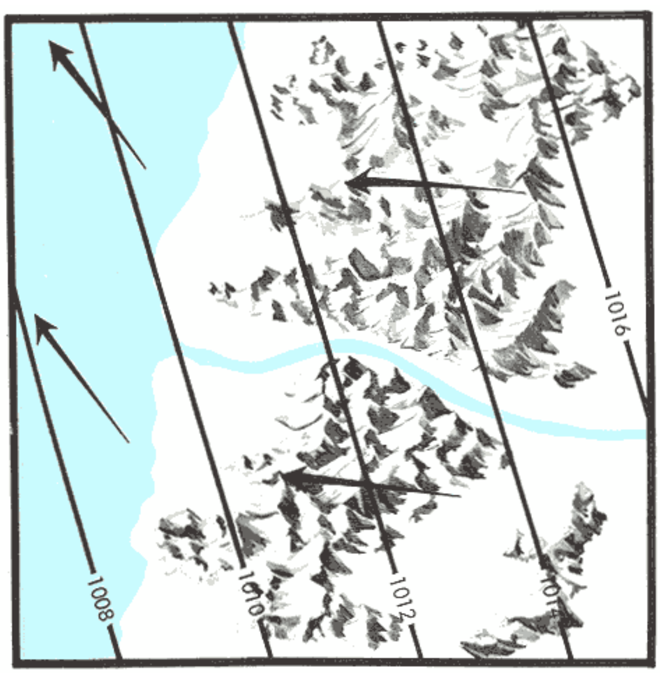
Mountain chains are also effective as solid barriers against airflow – particularly dry, cold air of polar origin and relatively cool Pacific marine air.

While warm, light air may be forced aloft and flow over the ranges, cool, heavy air is often either dammed or deflected by major mountain systems.

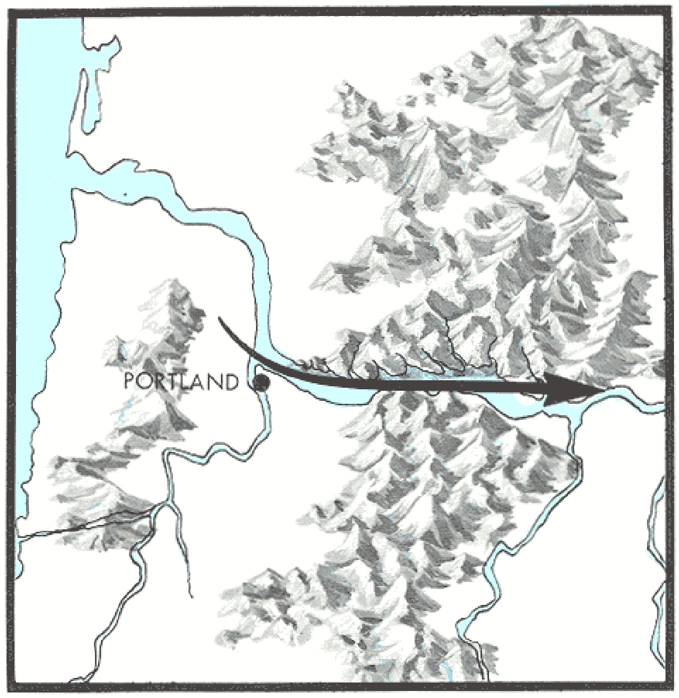
Over short distances and rough topography, gradient balance may not be established and winds of considerable speed may blow almost directly across isobars from higher to lower pressure. Winds of this nature are common in both coastal and inland mountain regions. This type of flow is particularly noticeable in the strong pressure-gradient region of a Santa Ana pattern.

Mountains and their associated valleys provide important channels that establish local wind direction. Airflow is guided by the topography into the principal drainage channels. Less-prominent features of the landscape have similar, though smaller scale, local mechanical effects on wind speed, direction, and turbulence. In short, winds blowing over the surface are influenced by every irregularity.

In addition to these mechanical effects, strong daytime convective activity in mountain areas often alters or replaces the general wind at the surface. General winds are most pronounced at the surface in the absence of strong heating.



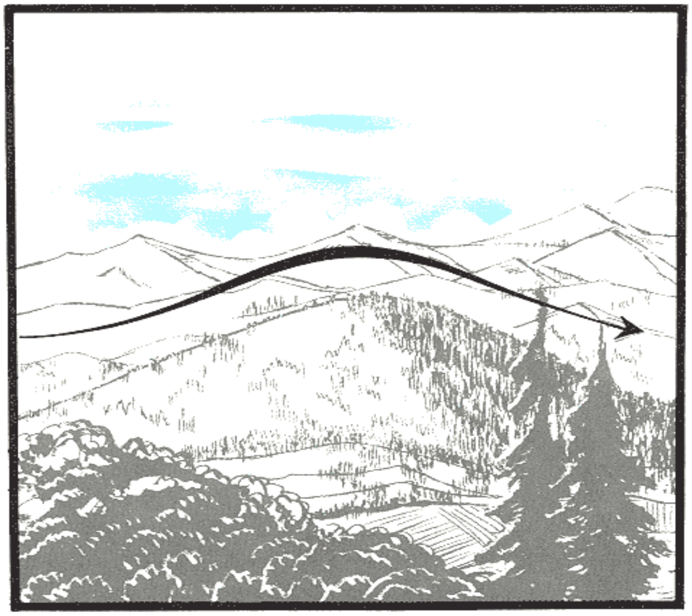
Over rough topography, large frictional effects may cause surface winds to blow almost directly across the isobars from high to low pressure. Where friction is less, such as over water, surface wind directions have only a small angle across the isobars.



Deep gorges in mountain ranges channel surface airflow.

General winds blowing across mountain ridges are lifted along the surface to the gaps and crests. If the air is stable, it will increase in speed as it crosses the ridge. Ridgetop winds thus tend to be somewhat stronger than winds in the free air at the same level.

How the air behaves on crossing a ridge is influenced by ridge shape and wind speed and direction. **Round-topped** ridges tend to disturb surface airflow the least. In light to moderate winds there is often little evidence of any marked turbulence. Sharp ridges, on the other hand, nearly always produce significant turbulence and numerous **eddies** on the lee side**.** Some of this is evident at the surface as gusts and eddies for short distances below the ridgetop, though much of it continues downwind aloft. Wind blowing perpendicular to the ridge line develops the least complex wind structure downwind, and most of the eddies formed are of the roll or horizontal type. If the angle of wind approach deviates from the perpendicular by some critical amount, perhaps 30° or less, vertical eddies are likely to be found in the lee draws below the ridgetop, in addition to eddies in other planes.



Airflow crossing a ridge is influenced by the ridge shape and by the wind speed and direction. Rounded hills disturb wind flow the least. In light to moderate winds, there may be no marked turbulence.

Higher wind speeds and sharp ridges cause turbulence and eddies on the lee side.

Eddy currents are often associated with bluffs and similarly shaped canyon rims. When a bluff faces downwind, air on the lee side is protected from the direct force of the wind flowing over the rim. If the wind is persistent, however, it may start to rotate the air below and form a large, stationary roll eddy. This often results in a moderate to strong upslope wind opposite in direction to that flowing over the rim. Eddies of this nature are common in

Large roll eddies are typical to the lee of bluffs or canyon rims. An upslope wind may be observed at the surface on the lee side.

the lee of ridges that break off abruptly, and beneath the rims of plateaus and canyon walls.

Ridgetop saddles and mountain passes form important channels for local pressure gradient winds. Flow converges here as it does across ridgetops, with an accompanying increase in wind speed. After passing through mountain saddles, the wind often exhibits two types of eddy motion on the lee side. One takes the form of horizontal eddies rolling or tumbling down the lee slope or canyon, although the main eddy may be stationary. The other is usually a stationary vertical eddy in one of the sheltered areas on either side of the saddle. Some of these vertical eddies may also move on downwind.

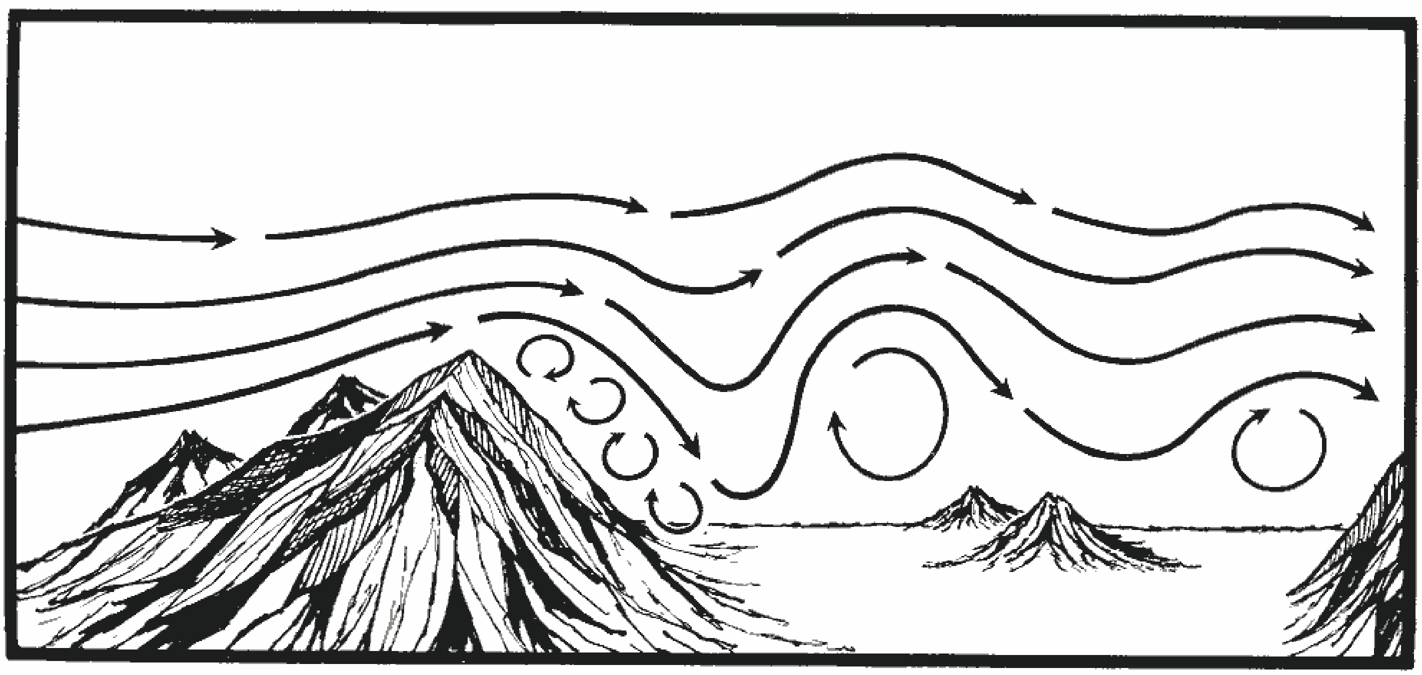
General winds that are channeled in mountain canyons are usually turbulent. The moving air in canyons is in contact with a maximum area of land surfaces. Alternating tributaries and lateral ridges produce maximum roughness. Whether the canyon bottom is straight or crooked also has an important influence on the turbulence to be expected. Sharp bends in mountain-stream courses are favorite "breeding grounds" for eddies, particularly where the canyon widens to admit a side tributary. Such eddies are most pronounced near the canyon floor and dissipate well below the ridgetop.

Eddies form where strong flow through canyons. Favorite places are bends in the canyons and mouths of tributaries.

Mountain Waves

Moderate to strong winds in a stably stratified atmosphere blowing across high mountain ranges will cause large-scale **mountain waves** for many miles downwind. The stable air, lifted by the wind over the mountain range, is pulled

Ridgetop saddles and mountain passes form important channels for general wind flow. The flow converges and the wind speed increases in the passes. Horizontal and vertical form on the lee side of saddles.



Mountain waves form when strong winds blow perpendicular to mountain ranges. Considerable turbulence and strong updrafts and downdrafts are found on the lee side. Crests of waves may be marked by lens-shaped wave clouds, but at times there may be insufficient moisture to form clouds.

downward by gravity on the lee side. Inertia carries the air past its equilibrium level, so it rises again farther downslope. This oscillatory motion forms a series of lesser waves downstream until the oscillation finally ceases. Waves may extend as high as 40,000 feet or more in the well-known Bishop wave in California. Large-scale waves occur in the Rocky Mountains, and waves on a lesser scale appear in the Appalachians and elsewhere.

The lee slope of the mountains may experience strong downslope winds or many eddies of various sizes which roll down the slope. Within each wave downstream from the mountain range, a large roll eddy may be found with its axis parallel to the mountain range. Roll eddies tend to be smaller in each succeeding wave downstream. The waves downwind of the mountains are referred to as lee waves or standing waves.

If sufficient moisture is present, cap clouds will form over the crest of the mountains, roll clouds will be found in the tops of the roll eddies downstream, and wave clouds will be located in the tops of the waves.

FOEHN WINDS

Foehn winds represent a special type of local wind associated with mountain systems. In most mountainous areas, local winds are observed that blow over the mountain ranges and descend the slopes on the leeward side. If the down flowing wind is warm and dry, it is called a foehn wind. The wind is called a bora or fall wind if the air is originally so cold that even after it is warmed adiabatically in flowing down the mountain slopes it is still colder than the air it is replacing on the leeward side. The been rarely occurs in North America and is not important in this discussion, because of its cold temperatures and the fact that the ground is often mow-covered when it occurs. We are concerned more with the warmer foehn, which creates a most critical fire-weather situation.

The development of a foehn wind requires a strong high-pressure system on one side of a mountain range and a corresponding Low or trough on the other side. Such pressure patterns are most common to the cool months; therefore, foehn winds are more frequent in the period from September through April than in the summer months. **Two types** of foehn winds are common in our western mountains.

Foehn winds of the first type result when a deep layer of moist air is forced upward and across a mountain range. As the air ascends the windward side, it is cooled dry-adiabatically until the condensation level is reached. Further lifting produces clouds and precipitation, and cooling at the lesser moist adiabatic rate. The water vapor that has condensed and fallen out as precipitation is lost to the air mass. Upon descending the leeward slopes, the air mass warms first at the moist-adiabatic rate until its clouds are evaporated. Then it warms at the dry-adiabatic rate and arrives at lower elevations both warmer and drier than it was at corresponding levels on the windward side. In descending to the lowlands on the leeward side of the range, the air arrives as a strong, gusty, desiccating wind.

Moist Pacific air forced across the Sierra - Cascade range loses some of its moisture and exhibits mild foehn characteristics on the eastern slopes. Forced across the Rocky Mountain range, the same air loses additional moisture and may produce a well-developed foehn on the eastern slopes in that region. The Plains east of the Rockies are often under the influence of a cold air mass of Canadian origin in the cooler months. If this air mass is then moved eastward by a favorable pressure gradient and replaced by a warm descending foehn, abrupt local temperature rises are experienced.

The **second** type of fusion is related to a cold, dry, usually stagnated high-pressure air mass restricted by mountain barriers. If a low pressure center or trough is located on the opposite side of the barrier, the strong pressure gradient will cause air to flow across the mountains. Since the mountains block the flow of surface air, the airflow must come from aloft. The air above the surface high-pressure system is subsiding air and is therefore dry and potentially quite warm. On the leeward side of the mountains, surface air is forced away by the strong pressure gradient, and it is replaced by the air flowing from aloft on the windward side and descending to the lowland on the leeward side. Surface wind speeds of 40 to 60 miles per hour are common in foehn flow of this type, and speeds up to 90 miles per hour have been reported

The wind often lasts for 3 days or more, with gradual weakening after the first day or two. Sometimes, it stops very abruptly.

High-pressure areas composed of cool air masses frequently stagnate in the Great Basin of the Western United States during the fall, winter, and spring months. Depending on its location, and the location of related Lows or troughs, a Great Basin High may create foehn winds which move eastward across the northern and central Rockies, westward across the Oregon and Washington Cascades and the northern and central Sierra Nevada, or southwestward across the Coast Ranges in southern California. A combination of high pressure over the State of Washington and low pressure in the Sacramento Valley causes north winds in northern California. Brief foehn wind periods, lasting 1 or 2 days, may result from migrating Highs passing through the Great Basin.

The course of the foehn may be either on a front many miles wide or a relatively narrow, sharply defined belt cutting through the lee-side air, depending on the pressure pattern and on the topography.

A foehn, even though it may be warm, often replaces cooler air on the lee side of the

Foehn winds are known by different names in different parts of the mountains West. In each case, air is flowing from a high-pressure area on the windward side of the mountains to a low-pressure area on the leeward side.

mountains. Counterforces sometimes prevent this, however, and cause the foehn to override the cooler air and thus not be felt at the surface at lower elevations. At other times the foehn may reach the surface only intermittently, or at scattered points, causing short-period fluctuations in local weather.

Two mechanisms come into play.

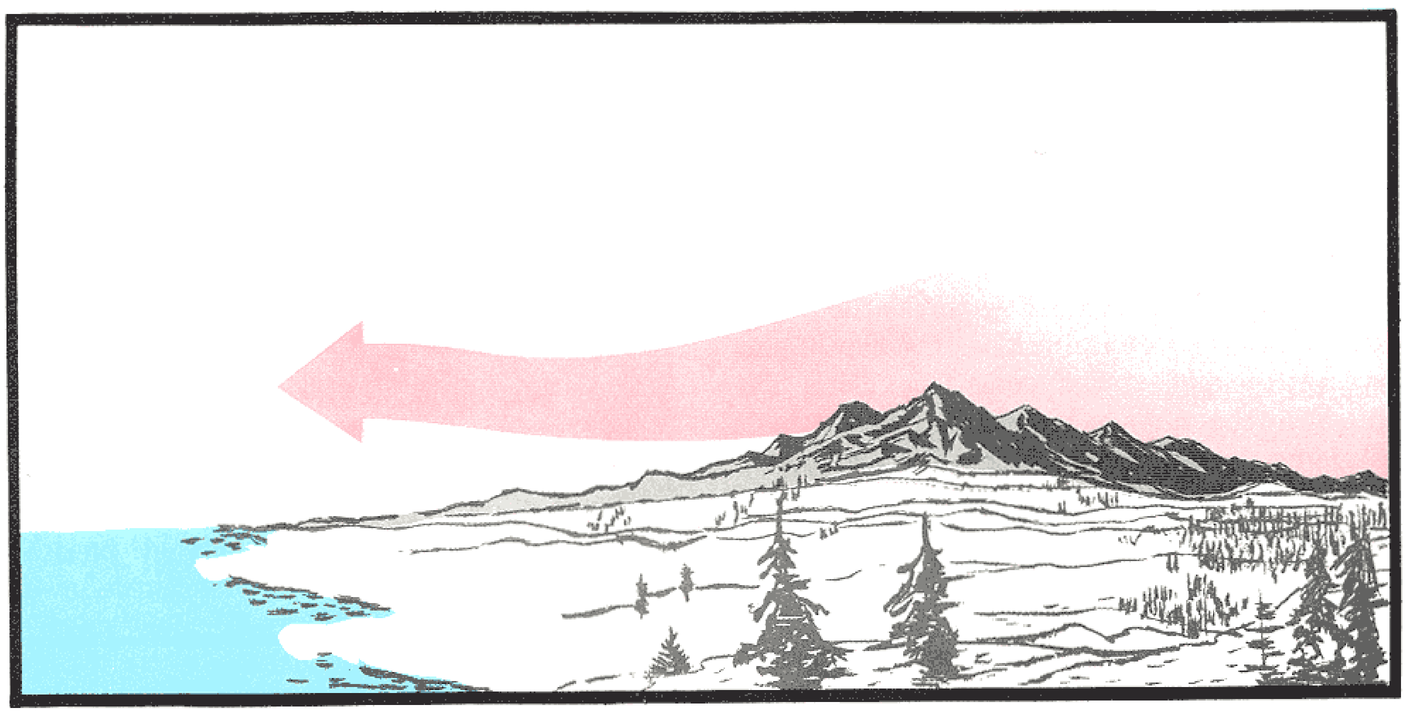
One is a **favorable pressure gradient** acting on the lee-side air in such a way as to move it away from the mountains so that the warm foehn can replace it.

A second mechanism is the **mountain wave** phenomenon. The wavelength and wave amplitude depend upon the strength of the flow bearing against the mountains and the stability of the layers in which the wave may be embedded. When these factors are favorable for producing waves which correspond to the shape of the mountain range, the foehn flow will follow the surface and produce strong surface winds on the lee slopes. There is evidence that strong downslope winds of the warm foehn on lee slopes are always caused by mountain waves. The change in wavelength and amplitude can account for the observed periodic surfacing and lifting of foehn flow. Surfacing often develops shortly after dark as cooling stabilizes the air crossing the ridge.

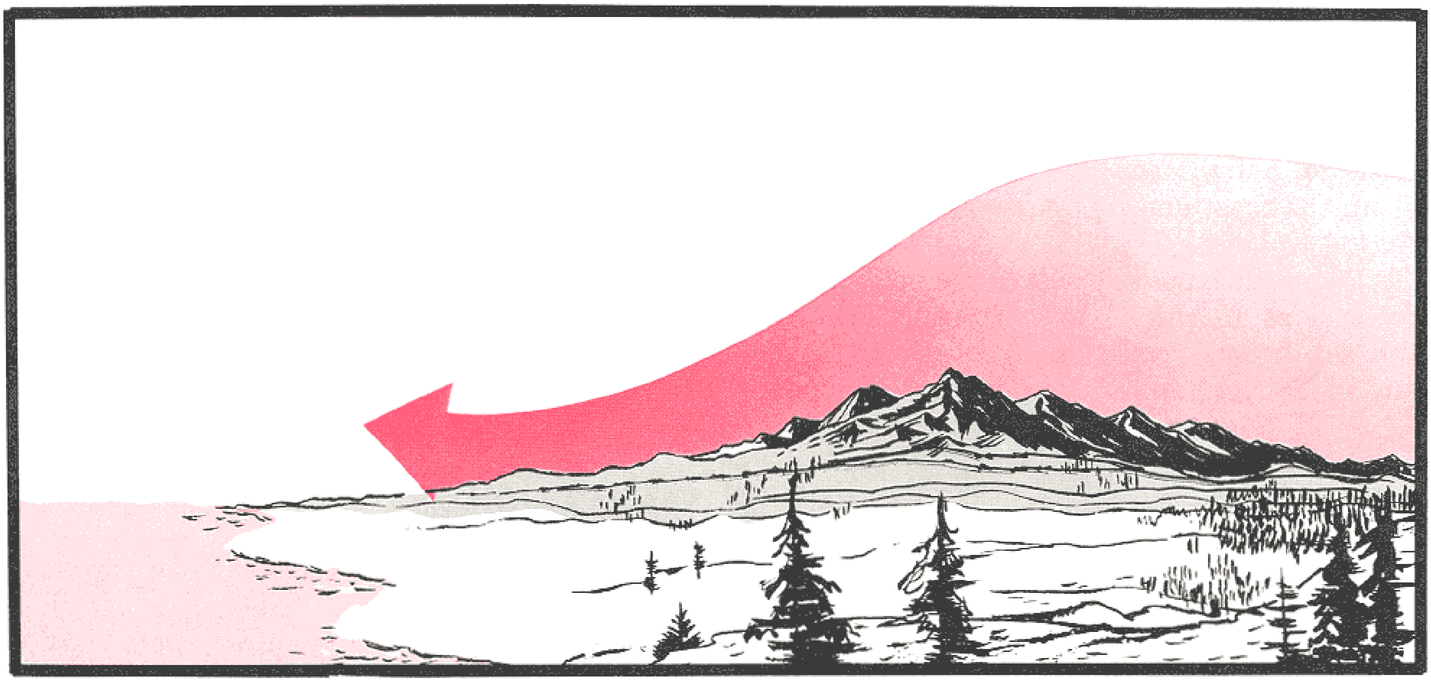
The Chinook, a foehn wind on the eastern slopes of the Rocky Mountains, often replaces cold continental air in Alberta and the Great Plains. Quick wintertime thawing and rapid snow evaporation are characteristic. If the cold air is held in place by the local pressure and circulation system, the foehn will override it; or if the cold air stays in the bottoms because of its greater density, the Chinook may reach the surface only in the higher spots. Relative humidities dropping to 5 percent or less and temperature changes of 30°F, to 40°F. within a few minutes are common in Chinooks.

Along the Pacific coast a weak foehn may be kept aloft by cool marine air flowing onshore. On the other hand, a strong, well-developed foehn may cut through all local influences and affect all slope and valley surfaces from the highest crest to the sea. **East winds** in the Pacific Northwest, for example, sometimes flow only part way down the lee slopes of the Cascades, and then level off above the lowlands and strike only the higher peaks and ridges of the coastal mountains. At other times virtually all areas are affected.

North and Mono winds in northern and central California develop as a High moves into the Great Basin. North winds develop if a High passes through Washington and Oregon



A weak foehn may override cooler air on the lee side of the mountains. In these cases only the higher elevations are affected by the foehn flow.



A strong foehn may flow down the leeward side of the mountains brining warm and extremely dry air to lower elevations. The air initially to the lee of the mountains is either moved away from the mountains by a favorable pressure gradient or it is scoured out by a suitable mountain – wave shape in the foehn flow. The foehn flow may surface and return aloft alternately in some foehn wind situations.

while a trough is located in the Sacramento Valley. Mono winds occur after the High has reached the Great Basin, providing there is a trough near the coast. Both North and Mono are foehn winds bringing warm, dry air to lower elevations. At times they will affect only the western slopes of the Sierra Nevada, and at other times they push across the coastal mountains and proceed out to sea. This depends upon the location of the low-pressure trough. These winds are most common in late summer and fall.

The Santa Areas of southern California also develop with a High in the Great Basin. The low-pressure trough is located along the southern California coast, and a strong pressure gradient is found across the southern California mountains.

In the coastal mountains, and the valleys, slopes, and basins on the ocean side, the Santa Ana varies widely. It is strongly channelled by the major passes, and, at times, bands of clear air can be seen cutting through a region of limited visibility. The flow coming over the tops of the ranges may remain aloft on the lee side or drop down to the surface, depending upon whether the Santa Ana is "strong" or "weak" and upon its mountain-wave characteristics. If the foehn flow is weak and remains aloft, only the higher elevations in the mountains are affected by the strong, dry winds. Local circulations, such as the sea breeze and slope winds, are predominant at lower elevations, particularly to areas away from the major passes.

Typically in southern California during the Santa Ana season, there is a daytime onshore breeze along the coast and gentle to weak upslope and upcanyon winds in the adjacent mountain areas. With nighttime cooling, these winds reverse in direction to produce downcanyon and offshore winds, usually of lesser magnitude than the daytime breeze. A strong Santa Ana wind wipes out these patterns. It flows over the ridges and down along the surface of leeward slopes and valleys and on to the sea. **The strong winds, along with warm temperatures and humidities sometimes lower than 5 percent, produce very serious fire weather in a region of flashy fuels.** The strong flow crossing the mountains creates mechanical turbulence, and many eddies of various sizes are produced by topographic features.

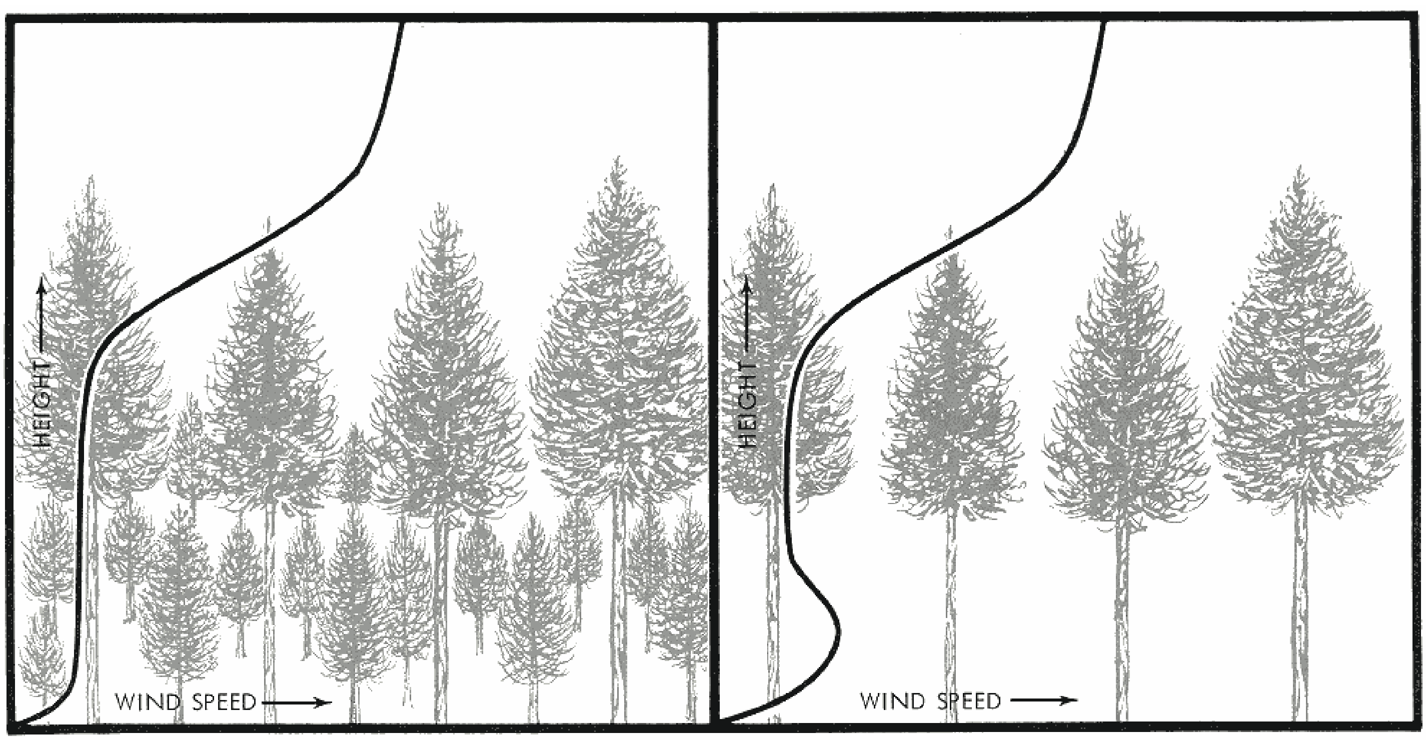
A strong Santa Ana, sweeping out the air ahead of it, often shows little or no difference in day and night behavior in its initial stages. But, after its initial surge, the Santa Ana begins to show a diurnal behavior. During the daytime, a light sea breeze may be observed along the coast and light upvalley winds in the coastal valleys. The Santa Ana flow is held aloft, and the mountain waves are not of proper dimensions to reach the surface. The air in the sea breeze may be returning Santa Ana air, which has had only a short trajectory over the water and is not as moist as marine air. After sunset, the surface winds reverse and become offshore and downslope. Increasing air stability may allow the shape of the mountain, waves to change so that the lower portions of waves can strike the surface and produce very strong winds down the lee slopes. As the Santa Ana continues to weaken, the local circulations become relatively stronger and finally the normal daily cycle is resumed.

EFFECTS OF VEGETATION

Vegetation is part of the friction surface which determines how the wind blows Lear the ground. Forests and other vegetated areas are characteristically rough surfaces and thus contribute to air turbulence, eddies, etc, They also have the distinction of being somewhat pervious, allowing some air movement through, as well as over and around, the vegetation.

Wind speeds over open, level ground, although zero at the very surface, increase quite rapidly in the first 20 feet above the ground. Where the surface is covered with low-growing, dense vegetation such as grass or brush, it is satisfactory, for most weather purposes, to consider the effective friction surface as the average height of the vegetation, disregarding the air flowing through it. In areas forested with trees, however, airflow within and below the tree canopies is important.

The leaf canopy in a forest is very effective in **slowing down** wind movements because of its large friction area. In forests of shade-tolerant



Vertical wind profiles in forest stands that the crown canopy is very effective in slowing down wind movement. In stands with an understory, the wind speed is nearly constant from just above the surface to near the tops of the crowns. Above the crowns, winds peed increases much like above level ground. In stands with an open trunk space, a maximum in wind speed is likely in the trunk space and a minimum in the crown area.

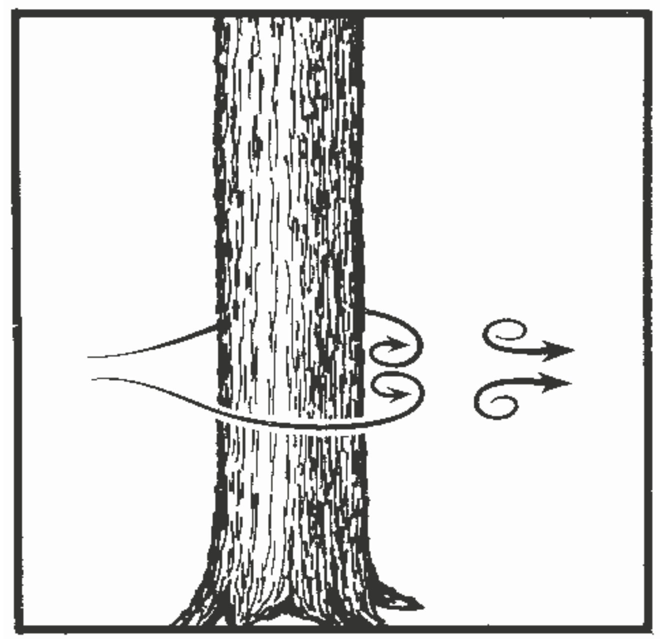
species where the canopy extends to near ground level, or in stands with understory vegetation, wind speed is nearly constant from just above the surface to near the tops of the crowns. Above the crowns, wind speed increases much as it does over level ground. In forest stands that are open beneath the main tree canopy, air speed increases with height above the surface to the middle of the trunk space, and then decreases again in the canopy zone,

How much the wind speed is reduced inside the forest depends on the detailed structure of the forest stand and on wind speed above the forest canopy, or as measured out in the open away from the forest. The drag of any friction surface is relatively much greater at high wind speeds than it is with low speeds. At low wind speeds, the forest may have only a small effect on the speed of the wind. For example, a 4-m.p.h. wind measured in the open might be slowed to 2.5-m.p.h. at the same height inside the forest. But a fairly high wind speed in the open will be slowed in the forest in much greater proportion. Thus, a 20-m.p.h. wind might be reduced to 4 - or 5 – m.p.h. in an 80-foot-tall stand of second-growth pine with normal stocking. The reduction would vary considerably, however, among different species and types of forest. Deciduous forests have a further seasonal variation, because although trees bare of leaves have a significant effect in limiting surface wind speeds, it is far less than when the trees are in full leaf.

Local eddies are common in forest stands and are found in the lee of each tree stem. These small eddies affect the behavior of surface fires.

Larger scale eddies often form in forest openings. The higher winds aloft cause the slower moving air in these openings to rotate about a vertical axis, or roll over in a horizontal manner. The surface wind direction is then frequently opposite to the direction above the treetops.

The edges of tree stands often cause roll eddies to form in the same manner as those



Local eddies form in the lee of each tree stem and affect the behavior of surface fires.

associated with bluffs. Wind blowing against the stand often produces small transient eddies on the windward side, while those in the lee of a forest are mostly larger and more fixed in location, with subeddies breaking off and moving downwind.

Strong surface heating, as on warm, sunny days, adds to the complexity of these forest airflow patterns. Thermal turbulence is added to the generally turbulent flow through open timber stands as it is to the flow above a closed forest canopy. The flow beneath a dense canopy is affected only slightly by thermal turbulence, except where holes let the sun strike bare ground or litter on the forest floor. These become hotspots over which there is a general upwelling of warm air through the canopy. This rising air is replaced by gentle inflow from surrounding shaded areas. Thermal turbulence on the lee side of a forest stand may often be enough to disguise or break up any roll eddies that tend to form.

SUMMARY

In this chapter we have discussed winds which are related to the large pressure patterns observed on synoptic-scale weather maps. We have seen that these general winds are strongly affected by the type of surface over which they flow, and that the amount of influence is largely dependent on the wind speed and the stability of the air. Stable air flowing over even surfaces tends to be smooth, or laminar. Unstable air or strong winds flowing over rough surfaces is turbulent and full of eddies.

Surface winds in the Northern Hemisphere tend to shift clockwise with the passage of fronts. In mountainous topography, however, the effect of the mountains on the windflow usually overshadows this. The windflow is channelled, and, over sharp crests, eddies are produced. At times, waves form over mountains, and, if conditions are favorable, strong surface winds are experienced on the lee side. When the airflow is from higher to lower elevations, the air warms adiabatically and foehn winds are produced. These winds have local names, such as Chinook, Santa Ana, etc., and are the cause of very severe fire weather.

In the next chapter we will consider local winds which result from local heating and cooling. They are called **convective winds, and** include such wind systems as mountain and valley winds, land and sea breezes, whirlwinds, and thunderstorm winds.