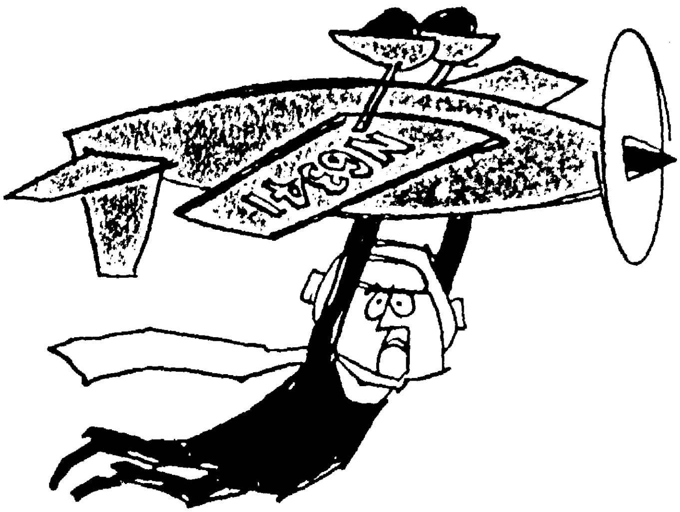

Chapter 9
TURBULENCE

Everyone who flies encounters turbulence at some time or other. A turbulent atmosphere is one in which air currents vary greatly over short distances. These currents range from rather mild eddies to strong currents of relatively large dimensions. As an aircraft moves through these currents, it undergoes changing accelerations which jostle it from its smooth flight path. This jostling is turbulence. Turbulence ranges from bumpiness which can annoy crew and passengers to severe jolts which can structurally damage the aircraft or injure its passengers.

Aircraft reaction to turbulence varies with the difference in windspeed in adjacent currents, size of the aircraft, wing loading, airspeed, and aircraft attitude. When an aircraft travels rapidly from one current to another, it undergoes abrupt changes in acceleration. Obviously, if the aircraft moved more slowly, the changes in acceleration would be more gradual. The first rule in flying turbulence is to reduce airspeed. Your aircraft manual most likely lists recommended airspeed for penetrating turbulence.

Knowing where to expect turbulence helps a pilot avoid or minimize turbulence discomfort and hazards. The main causes of turbulence are (1) convective currents, (2) obstructions to wind flow, and (3) wind shear. Turbulence also occurs in the wake of moving aircraft whenever the airfoils exert lift—wake turbulence. Any combination of causes may occur at one time.

CONVECTIVE CURRENTS

Convective currents are a common cause of turbulence, especially at low altitudes. These currents are localized vertical air movements, both *ascending* and *descending*. For every rising current, there

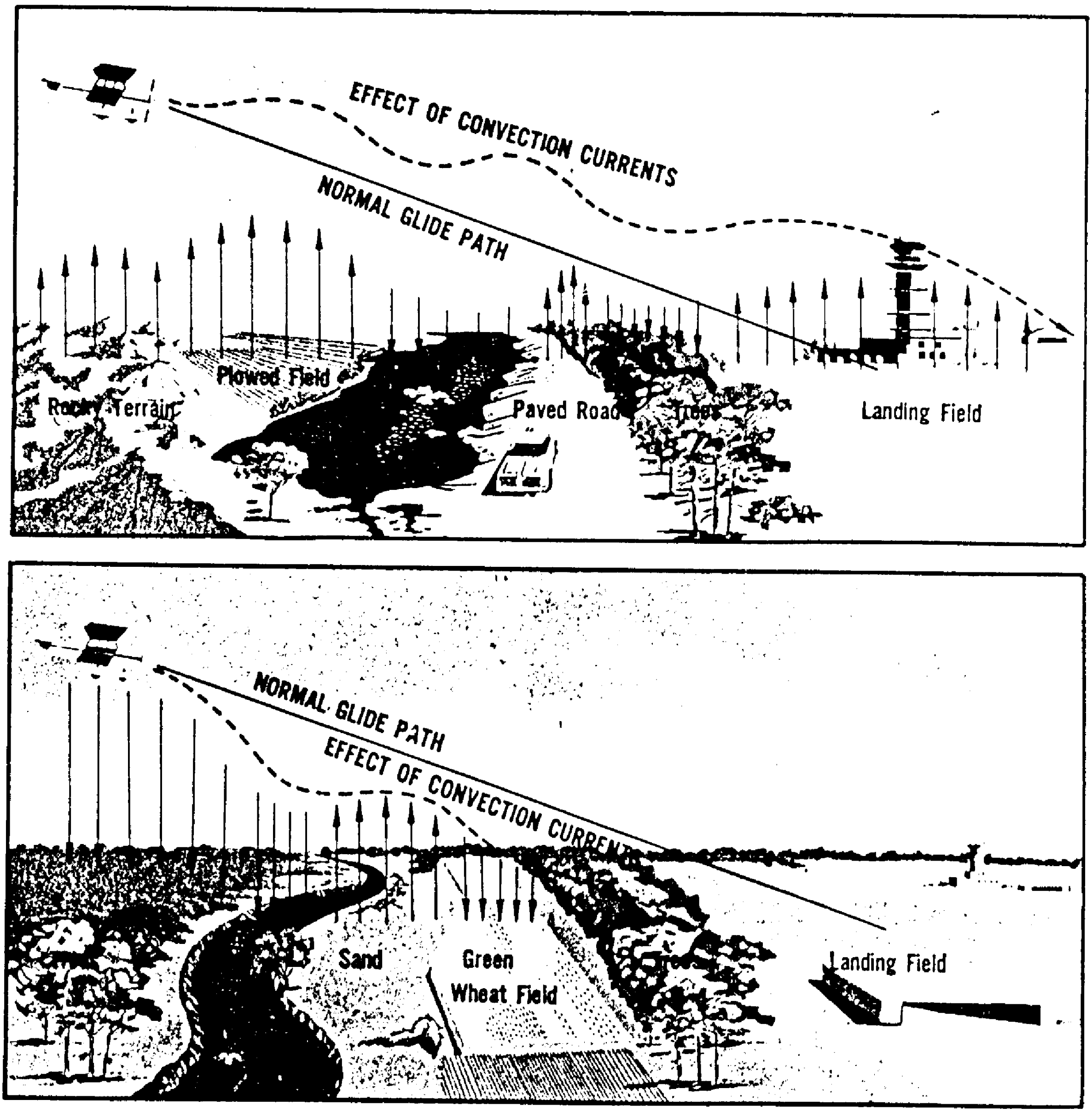

FIGURE 76. Effect of convective currents on final approach. Predominantly upward currents (top) tend to cause the aircraft to overshoot. Predominantly downward currents (bottom) tend to cause the craft to undershoot.

is a compensating downward current. The downward currents frequently occur over broader areas than do the upward currents, and therefore, they have a slower vertical speed than do the rising currents.

Convective currents are most active on warm summer afternoons when winds are light. Heated air at the surface creates a shallow, unstable layer, and the warm air is forced upward. Convection increases in strength and to greater heights as surface heating increases. Barren surfaces such as sandy or rocky wastelands and plowed fields become hotter than open water or ground covered by vegetation. Thus, air at and near the surface heats unevenly. Because of uneven heating, the strength of convective currents can vary considerably within short distances.

When cold air moves over a warm surface, it becomes unstable in lower levels. Convective currents extend several thousand feet above the surface resulting in rough, choppy turbulence when flying in the cold air. This condition often occurs in any season after the passage of a cold front.

Figure 76 illustrates the effect of low-level convective turbulence on aircraft approaching to land. Turbulence on approach can cause abrupt changes in airspeed and may even result in a stall at a dangerously low altitude. To prevent the danger, increase airspeed slightly over normal approach speed. This procedure may appear to conflict with the rule of reducing airspeed for turbulence penetration; but remember, the approach speed for your aircraft is well below the recommended turbulence penetration speed.

As air moves upward, it cools by expansion. A convective current continues upward until it reaches a level where its temperature cools to the same as that of the surrounding air. If it cools to saturation, a cloud forms. Billowy fair weather cumulus clouds, usually seen on sunny afternoons, are signposts in the sky indicating convective turbulence. The cloud top usually marks the approximate upper limit of the convective current. A pilot can expect to encounter turbulence beneath or in the clouds, while above the clouds, air generally is smooth. You will find most comfortable flight above the cumulus as illustrated in figure 77.

When convection extends to greater heights, it develops larger towering cumulus clouds and cumulonimbus with anvil-like tops. The cumulonimbus gives visual warning of violent convective turbulence discussed in more detail in chapter 11.

The pilot should also know that when air is too dry for cumulus to form, convective currents still can be active. He has little indication of their presence until he encounters turbulence.

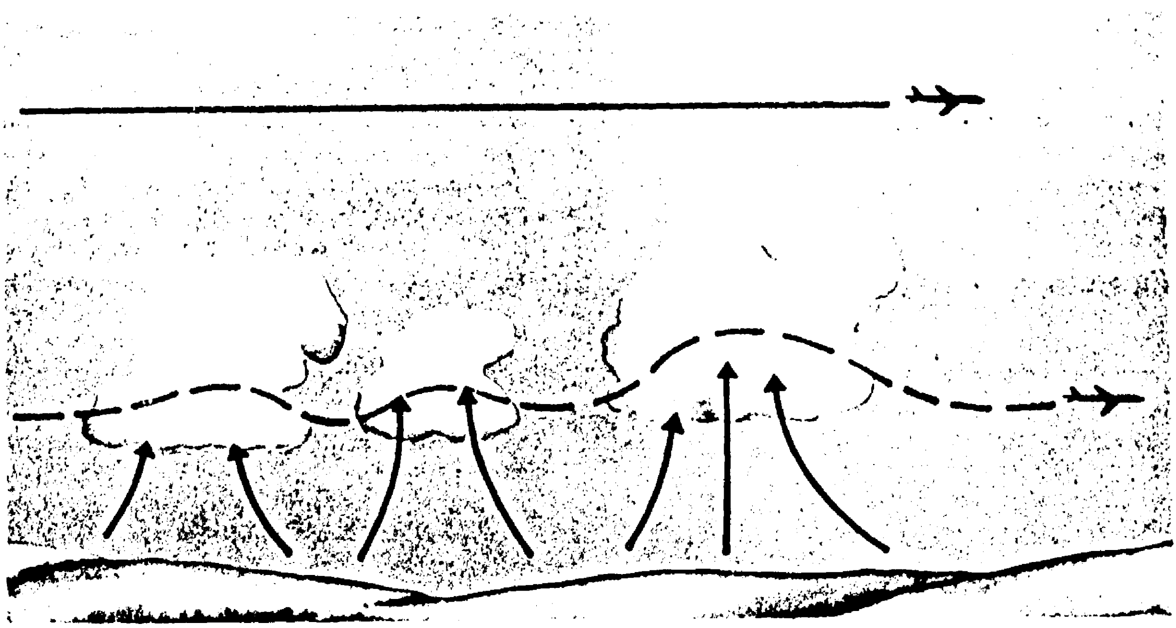

FIGURE 77. Avoiding turbulence by flying above convective clouds.

OBSTRUCTIONS TO WIND FLOW

Obstructions such as buildings, trees, and rough terrain disrupt smooth wind flow into a complex snarl of eddies as diagrammed in figure 78. An aircraft flying through these eddies experiences turbulence. This turbulence we classify as "mechanical" since it results from mechanical disruption of the ambient wind flow.

The degree of mechanical turbulence depends on wind speed and roughness of the obstructions. The higher the speed and/or the rougher the surface, the greater is the turbulence. The wind carries the turbulent eddies downstream—how far depends on wind speed and stability of the air. Unstable air allows larger eddies to form than those that form in stable air; but the instability breaks up the eddies quickly, while in stable air they dissipate slowly.

Mechanical turbulence can also cause cloudiness near the top of the mechanically disturbed layer. However, the type of cloudiness tells you whether

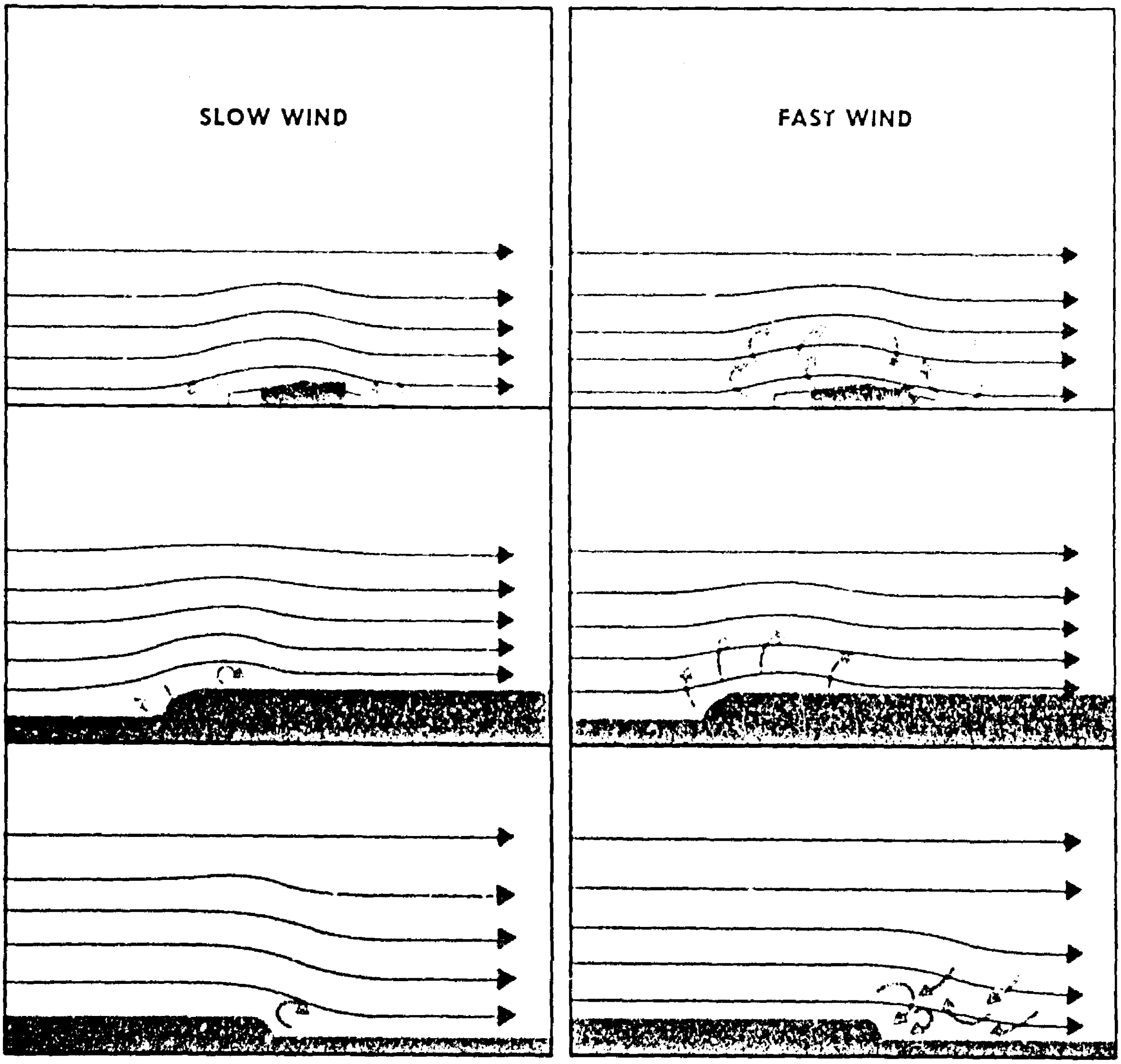

FIGURE 78. Eddy currents formed by wind blowing over uneven ground or over obstructions.

it is from mechanical or convective mixing. Mechanical mixing produces stratocumulus clouds in rows or bands, while convective clouds form a random pattern. The cloud rows developed by mechanical mixing may be parallel to or perpendicular to the wind depending on meteorological factors which we do not discuss here.

The airport area is especially vulnerable to mechanical turbulence which invariably causes gusty surface winds. When an aircraft is in a low-level approach or a climb, airspeed fluctuates in the gusts, and the aircraft may even stall. During extremely gusty conditions, maintain a margin of airspeed above normal approach or climb speed to allow for changes in airspeed. When landing with a gusty crosswind as illustrated in figure 79, be alert for mechanical turbulence and control problems caused by airport structures upwind. Surface gusts also create taxi problems.

Mechanical turbulence can affect low-level cross-country flight about anywhere. Mountains can generate turbulence to altitudes much higher than the mountains themselves.

When flying over rolling hills, you may experience mechanical turbulence. Generally, such turbulence is not hazardous, but it may be annoying or uncomfortable. A climb to higher altitude should reduce the turbulence.

When flying over rugged hills or mountains, however, you may have some real turbulence problems. Again, we cannot discuss mechanical turbulence without considering wind speed and stability. When wind speed across mountains exceeds about 40 knots, you can anticipate turbulence. Where and to what extent depends largely on stability.

If the air crossing the mountains is unstable, turbulence on the windward side is almost certain. If sufficient moisture is present, convective clouds form intensifying the turbulence. Convective clouds over a mountain or along a ridge are a sure sign of unstable air and turbulence on the windward side and over the mountain crest.

As the unstable air crosses the barrier, it spills down the leeward slope often as a violent downdraft. Sometimes the downward speed exceeds the maximum climb rate for your aircraft and may drive the craft into the mountainside as shown in figure 80. In the process of crossing the mountains, mixing reduces the instability to some extent. Therefore, hazardous turbulence in unstable air generally does not extend a great distance downwind from the barrier.

MOUNTAIN WAVE

When stable air crosses a mountain barrier, the turbulent situation is somewhat reversed. Air flowing up the windward side is relatively smooth. Wind flow across the barrier is laminar—that is, it tends to flow in layers. The barrier may set up waves in these layers much as waves develop on

FIGURE 79. Turbulent air in the landing area.

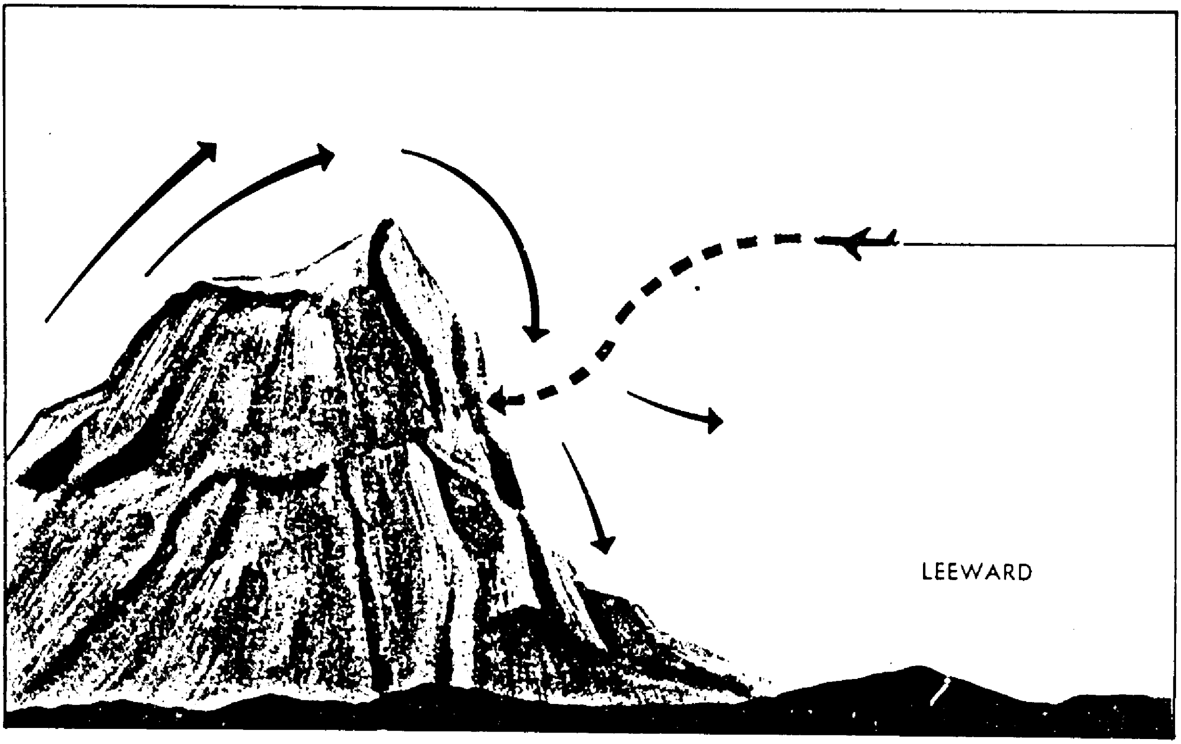

FIGURE 80. Wind flow in mountain areas. Dangerous downdrafts may be encountered on the lee side.

a disturbed water surface. The waves remain nearly stationary while the wind blows rapidly through them. The wave pattern, diagrammed in figure 81, is a "standing" or "mountain" wave, so named because it remains essentially stationary and is associated with the mountain. The wave pattern may extend 100 miles or more downwind from the barrier.

Wave crests extend well above the highest mountains, sometimes into the lower stratosphere. Under

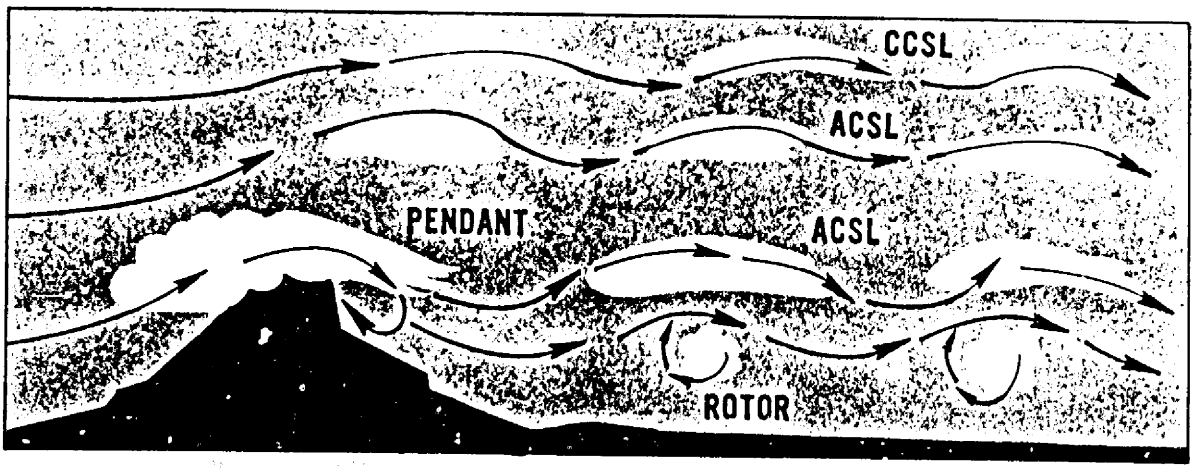

FIGURE 81. Schematic cross section of a mountain wave. Note the standing wave pattern downwind from the mountain. Note also the rotary circulation below the wave crests. When the air contains sufficient moisture, characteristic clouds form.

each wave crest is a rotary circulation also diagrammed in figure 81. The "rotor" forms below the elevation of the mountain peaks. Turbulence can be violent in the overturning rotor. Updrafts and downdrafts in the waves can also create violent turbulence.

Figure 81 further illustrates clouds often associated with a mountain wave. When moisture is sufficient to produce clouds on the windward side, they are stratified. Crests of the standing waves may be marked by stationary, lens-shaped clouds known as "standing lenticular" clouds. Figure 82 is a photograph of standing lenticular clouds. They form in the updraft and dissipate in the downdraft, so they do not move as the wind blows through them. The rotor may also be marked by a "rotor" cloud. Figure 83 is a photograph of a series of rotor clouds, each under the crest of a wave. But remember, clouds are not always present to mark the mountain wave. Sometimes, the air is too dry. Always anticipate possible mountain wave turbulence when strong winds of 40 knots or greater blow across a mountain or ridge and the air is stable.

You should not be surprised at any degree of turbulence in a mountain wave. Reports of turbulence range from none to turbulence violent enough to damage the aircraft, but most reports show something in between.

MOUNTAIN FLYING

When planning a flight over mountainous terrain, gather as much preflight information as possible on cloud reports, wind direction, wind speed, and stability of air. Satellites often help locate mountain waves. Figures 84 and 85 are photographs of mountain wave clouds taken from spacecraft. Adequate information may not always be available, so remain alert for signposts in the sky. What should you look for both during preflight planning and during your inflight observations?

Wind at mountain top level in excess of 25 knots suggests some turbulence. Wind in excess of 40 knots across a mountain barrier dictates caution. Stratified clouds mean stable air. Standing lentic-

FIGURE 82. Standing lenticular clouds associated with a mountain wave.

Figure 83. Standing wave rotor clouds marking the rotary circulation beneath mountain waves.

ular and/or rotor clouds suggest a mountain wave; expect turbulence many miles to the lee of mountains and relative smooth flight on the windward side. Convective clouds on the windward side of mountains mean unstable air; expect turbulence in close proximity to and on either side of the mountain.

When approaching mountains from the leeward side during strong winds, begin your climb well away from the mountains—100 miles in a mountain wave and 30 to 50 miles otherwise. Climb to an altitude 3,000 to 5,000 feet above mountain tops before attempting to cross. The best procedure is to approach a ridge at a 45° angle to enable a rapid retreat to calmer air. If unable to make good on your first attempt and you have higher altitude capabilities, you may back off and make another attempt at higher altitude. Sometimes you may have to choose between turning back or detouring the area.

Flying mountain passes and valleys is not a safe procedure during high winds. The mountains funnel the wind into passes and valleys thus increasing wind speed and intensifying turbulence. If winds at mountain top level are strong, go high, or go around.

Surface wind may be relatively calm in a valley surrounded by mountains when wind aloft is strong. If taking off in the valley, climb above mountain top level before leaving the valley. Maintain lateral clearance from the mountains sufficient to allow recovery if caught in a downdraft.

WIND SHEAR

As discussed in chapter 4, wind shear generates eddies between two wind currents of differing velocities. The differences may be in wind speed, wind direction, or in both. Wind shear may be associated with either a wind shift or a wind speed gradient at any level in the atmosphere. Three conditions are of special interest—(1) wind shear with a low-level temperature inversion, (2) wind shear

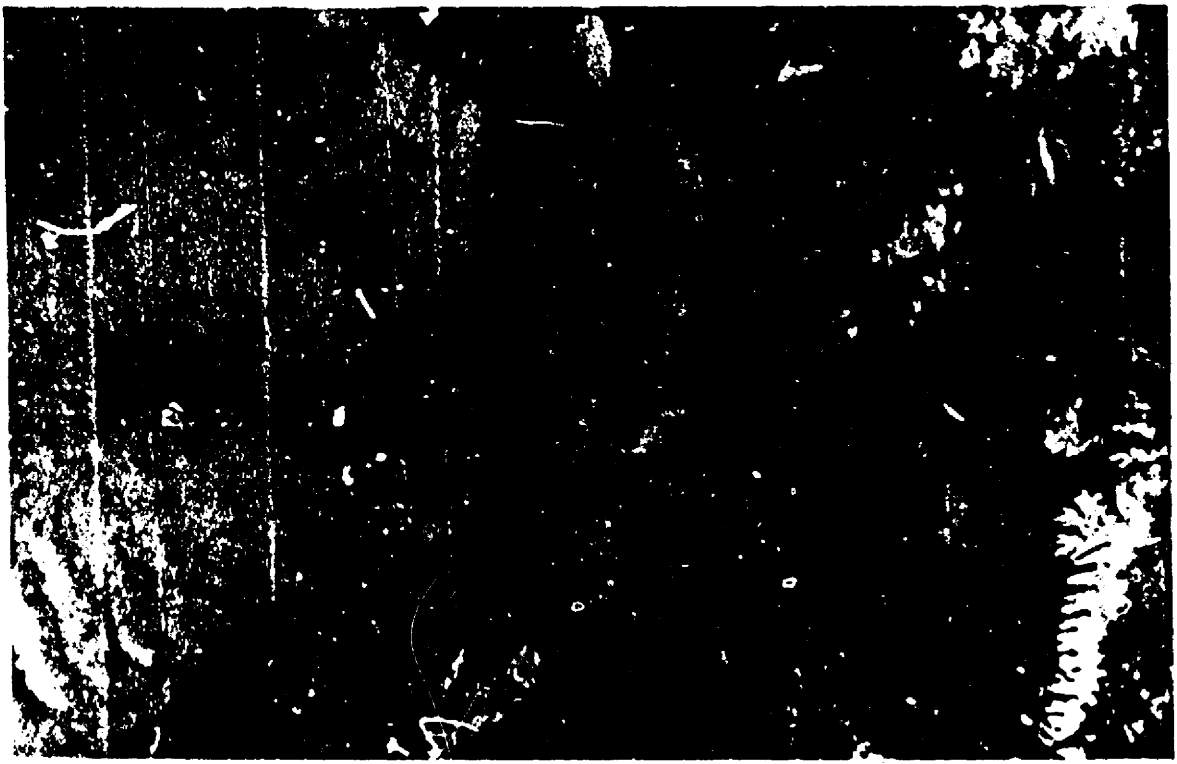

FIGURE 84. Mountain wave clouds over the Tibetan Plateau photographed from a manned spacecraft.

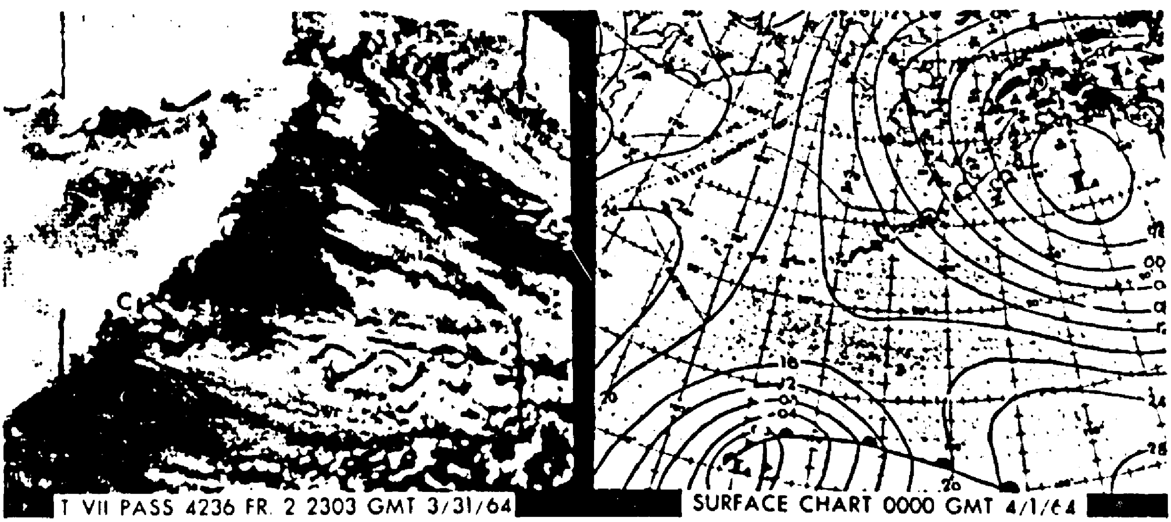

FIGURE 85. Satellite photograph of a mountain wave and the surface weather map for approximately the same time. A single mountain in the Aleutian chain generates the wave. Note how it spirals downwind from the source. Without the satellite, the turbulent wave would have gone undetected unless some aircraft had flown into it.

in a frontal zone, and (3) clear air turbulence (CAT) at high levels associated with a jet stream or strong circulation. High-level clear air turbulence is discussed in detail in chapter 13, "High Altitude Weather."

WIND SHEAR WITH A LOW-LEVEL TEMPERATURE INVERSION

A temperature inversion forms near the surface on a clear night with calm or light surface wind as discussed in chapter 2. Wind just above the inversion may be relatively strong. As illustrated in figure 86, a wind shear zone develops between the calm and the stronger winds above. Eddies in the shear zone cause airspeed fluctuations as an aircraft climbs or descends through the inversion. An aircraft most likely is either climbing from takeoff or approaching to land when passing through the inversion; therefore, airspeed is slow—only a few knots greater than stall speed. The fluctuation in airspeed can induce a stall precariously close to the ground.

Since surface wind is calm or very light, takeoff or landing can be in any direction. Takeoff may be in the direction of the wind above the inversion. If so, the aircraft encounters a sudden tailwind and a corresponding loss of airspeed when climbing through the inversion. Stall is possible. If approach is into the wind above the inversion, the headwind is suddenly lost when descending through the inversion. Again, a sudden loss in airspeed may induce a stall.

When taking off or landing in calm wind under clear skies within a few hours before or after sunrise, be prepared for a temperature inversion near the ground. You can be relatively certain of a shear zone in the inversion if you know the wind at 2,000 to 4,000 feet is 25 knots or more. Allow a margin of airspeed above normal climb or approach speed to alleviate danger of stall in event of turbulence or sudden change in wind velocity.

WIND SHEAR IN A FRONTAL ZONE

As you have learned in chapter 8, a front can contain many hazards. However, a front can be between two dry stable airmasses and can be devoid of clouds. Even so, wind changes abruptly in the frontal zone and can induce wind shear turbulence. The degree of turbulence depends on the magnitude of the wind shear. When turbulence is expected in a frontal zone, follow turbulence penetration procedures recommended in your aircraft manual.

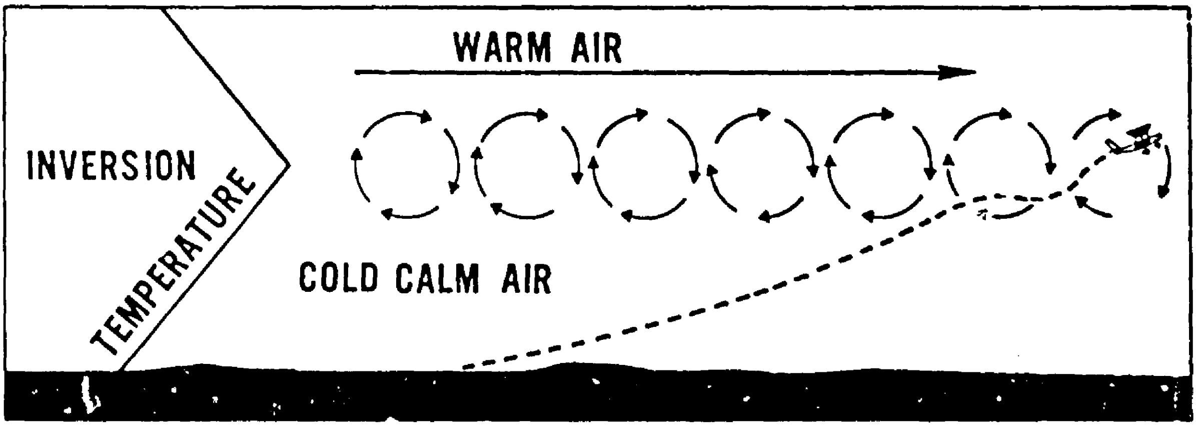

FIGURE 86. Wind shear in a zone between relatively calm wind below an inversion and strong wind above the inversion. This condition is most common at night or in early morning. It can cause an abrupt turbulence encounter at low altitude.

WAKE TURBULENCE

An aircraft receives its lift by accelerating a mass of air downward. Thus, whenever the wings are providing lift, air is forced downward under the wings generating rotary motions or vortices off the wing tips. When the landing gear bears the entire weight of the aircraft, no wing tip vortices develop. But the instant the pilot "hauls back" on the controls, these vortices begin. Figure 87 illustrates how they might appear if visible behind the plane as it breaks ground. These vortices continue throughout the flight and until the craft again settles firmly on its landing gear.

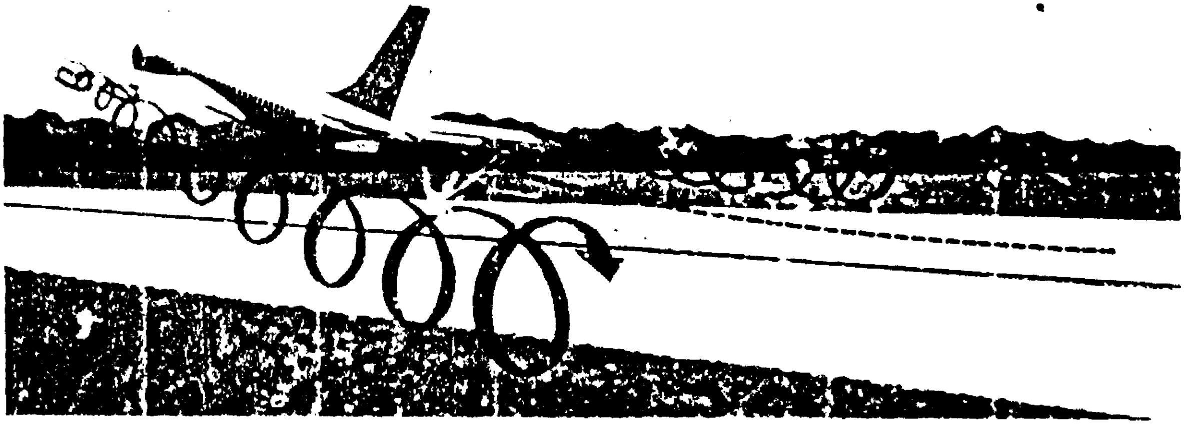

FIGURE 87. Wake turbulence wing tip vortices developing as aircraft breaks ground. These vortices develop when the aircraft is rotated into a flying attitude and the wings begin developing lift.

These vortices spread downward and outward from the flight path. They also drift with the wind. Strength of the vortices is proportional to the weight of the aircraft as well as other factors. Therefore wake turbulence is more intense behind large, transport category aircraft than behind small aircraft. Generally, it is a problem only when following the larger aircraft.

The turbulence persists several minutes and may linger after the aircraft is out of sight. At controlled airports, the controller generally warns pilots in the vicinity of possible wake turbulence. When left to your own resources, you could use a few pointers. Most jets when taking off lift the nose wheel about midpoint in the takeoff roll; therefore, vortices begin about the middle of the takeoff roll. Vortices behind propeller aircraft begin only a short distance behind lift-off. Following a landing of either type of aircraft, vortices end at about the point where the nose wheel touches down. Avoid flying through these vortices. More specifically, when using the same runway as a heavier aircraft:

(1) if landing behind another aircraft, keep your approach above his approach and keep your touchdown beyond the point where his nose wheel touched the runway (figure 88 (A));

(2) if landing behind a departing aircraft, land only if you can complete your landing roll before reaching the midpoint of his takeoff roll (figure 88 (B));

(3) if departing behind another departing aircraft, take off only if you can become airborne before reaching the midpoint of his takeoff roll and only if you can climb fast enough to stay above his flight path (figure 88 (C)); and

(4) if departing behind a landing aircraft, don't unless you can taxi onto the runway beyond the point at which his nose wheel touched down and have sufficient runway left for safe takeoff (figure 88 (D)).

If parallel runways are available and the heavier aircraft takes off with a crosswind on the downwind runway, you may safely use the upwind runway. Never land or take off downwind from the heavier aircraft. When using a runway crossing his runway, you may safely use the upwind portion of your runway. You may cross behind a departing aircraft behind the midpoint of his takeoff roll. You may cross ahead of a landing aircraft ahead of the point at which his nose wheel touches down. If none of these procedures is possible, wait 5 minutes or so for the vortices to dissipate or to blow off the runway.

The foregoing procedures are elementary. The problem of wake turbulence is more operational than meteorological. The FAA issues periodic ad-

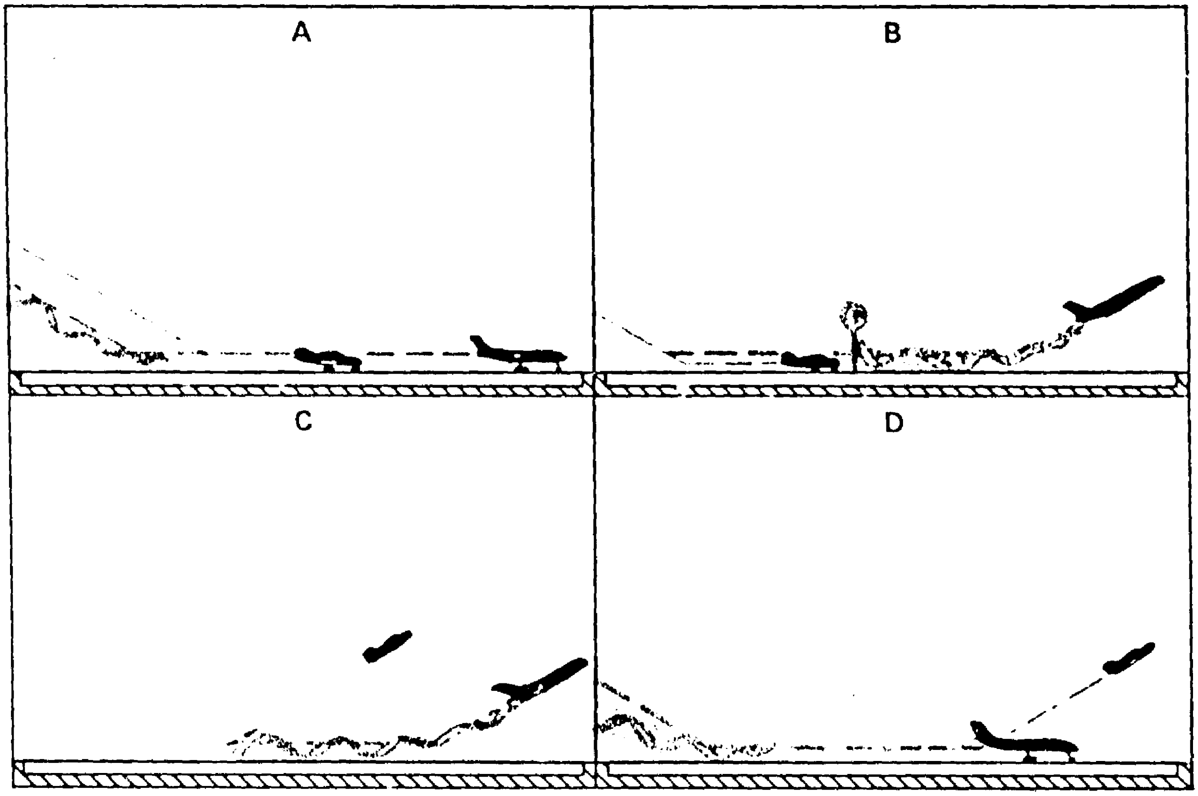

FIGURE 88. Planning landing or takeoff to avoid heavy aircraft wake turbulence.

visory circulars of operational problems. If you plan to operate out of airports used routinely by air carriers, we highly recommend you read the latest advisory circulars on wake turbulence. Titles of these circulars are listed in the FAA "Advisory Circular Checklist and Status of Regulations."

IN CLOSING

We have discussed causes of turbulence, classified it into types, and offered some flight procedures to avoid it or minimize its hazards. Occurrences of turbulence, however, are local in extent and transient in character. A forecast of turbulence specifies a volume of airspace that is small when compared to useable airspace but relatively large compared to the localized extent of the hazard. Although general forecasts of turbulence are quite good, forecasting precise locations is at present impossible.

Generally, when a pilot receives a forecast, he plans his flight to avoid areas of *most probable turbulence*. Yet the best laid plans can go astray and he may encounter turbulence. Since no instruments are currently available for directly observing turbulence, the man on the ground can only confirm its existence or absence via pilot reports.

HELP YOUR FELLOW PILOT AND THE WEATHER SERVICE—SEND PILOT REPORTS.

To make reports and forecasts meaningful, turbulence is classified into intensities based on the effects it has on the aircraft and passengers. Section 16 of AVIATION WEATHER SERVICES (AC 00-45) lists and describes these intensities. Use this guide in reporting your turbulence encounters.