AC 00-57

Hazardous Mountain Winds

And Their Visual Indicators

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U.S. DEPARTMENT OF TRANSPORTATION
Federal Aviation Administration
Office of Communications, Navigation, and Surveillance Systems
Washington, D.C.

FOREWORD

This advisory circular (AC) contains information on hazardous mountain winds and their effects on flight operations near mountainous regions. The primary purpose of this AC is to assist pilots involved in aviation operations to diagnose the potential for severe wind events in the vicinity of mountainous areas and to provide information on pre-flight planning techniques and in-flight evaluation strategies for avoiding destructive turbulence and loss of aircraft control. Additionally, pilots and others who must deal with weather phenomena in aviation operations also will benefit from the information contained in this AC.

Pilots can review the photographs and section summaries to learn about and recognize common indicators of wind motion in the atmosphere. The photographs show physical processes and provide visual clues. The summaries cover the technical and "wonder" aspects of why certain things occur — what caused it? How does it affect pre-flight and in-flight decisions? The physical aspects are covered more in-depth through the text.

Comments regarding this publication should be directed to the Department of Transportation, Federal Aviation Administration, Flight Standards Service, Technical Programs Division, 800 Independence Avenue, S.W. Washington, DC 20591.

Acknowledgments

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Cover photo: over Boulder, Colorado,
winter 1988,

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PART I. REVIEW OF METEOROLOGICAL CONCEPTS

1.0 INTRODUCTION

Flight in the vicinity of mountainous terrain can be inspiring and immensely enjoyable for both pilots and passengers. However, this aspect of aviation also can present pilots with some of the most challenging and potentially dangerous situations encountered in air operations. Aircraft performance degradation because of high density altitudes, navigation problems associated with en route terrain obstructions, and rapidly changing weather patterns can cause difficulties for pilots of smaller aircraft operating at lower altitudes. In addition, the crews of high performance turbine equipment must deal with high altitude turbulence as well as reductions in aircraft performance caused by density altitude conditions. All pilots who fly near mountainous terrain must deal with the potential for mountain-induced severe wind events, particularly during takeoff and landing. Although the effects of density altitude and high terrain are of great importance to all pilots who are operating in mountainous areas, our discussion here is limited to the hazardous effects of mountainous weather systems on aircraft operations.

The atmosphere is a fluid in motion. Just as the swiftly flowing water in a stream develops waves and eddies as it passes over and around obstructions, so does the atmosphere contain disturbances that develop as it interacts with mountainous terrain. These atmospheric eddies can range in size from a few centimeters to tens or hundreds of kilometers, and can present the pilot with relatively smooth air, or with turbulence of potentially destructive intensity, and the likelihood of loss of control. The mountain-induced flow fields we will discuss in this AC are frequently accompanied by visual indicators (such as lenticular and rotor clouds or blowing dust). However, this is not always the case, and extremely severe wind events can occur with little or no visual warning of their presence.

The purpose of this AC is to assist pilots, and others involved in aviation operations, in diagnosing the potential for severe wind events in the vicinity of mountainous areas and to provide information on pre-flight planning techniques and in-flight evaluation strategies for avoiding destructive turbulence and loss of aircraft control. This AC can be used in several ways. For those readers who wish to obtain a more detailed understanding of the phenomena, the AC

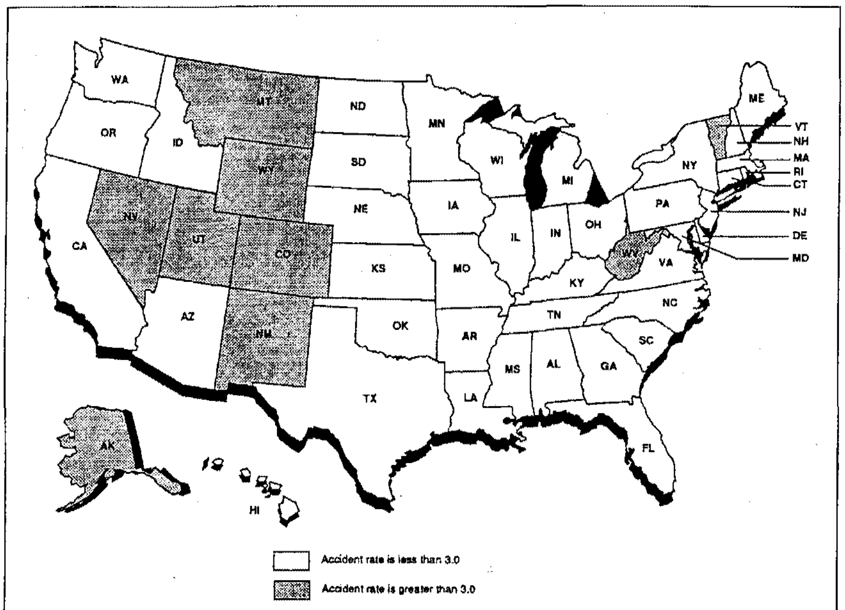


Figure 1-1. States with general aviation accident rates over 3.0 per 100,000 operations, Fiscal Year 1992.

discusses meteorological theory relating to the development of each type of severe wind event. It then provides descriptive summaries (in boxes) of the major points developed for each weather hazard. Those who desire only the latter information can omit the background theory. Finally, an atlas of visual indicators has been included to allow the reader to visually identify the cloud formations in question.

Several points should be noted before we proceed. The first is that we understand a good deal about the mechanisms involved in the production of mountain-related meteorological disturbances at the larger end of the wavelength spectrum, such as lee waves. However, the role of pulsations in the wind over and around mountain peaks in producing extremely strong, small-scale eddies, and the range of strengths of those disturbances are not well understood. **Second, it should be remembered that all information contained in this AC is advisory in nature and based upon our current level of knowledge. Individual pilot actions, as set forth under the Federal Aviation Regulations, are strictly the decision of the pilot in command based upon his or her best evaluation of the existing conditions and the performance characteristics of the aircraft.**

It is hoped that this document represents the first edition of what will become a succession of training resources for aircrews and other aviation professionals, with revisions based on the results of planned research. For now, it cannot be stressed too strongly that much is yet to be learned about the atmosphere as it interacts with high terrain.

2.0 ACCIDENT STATISTICS

Numerous aircraft accidents have occurred over mountainous areas involving general aviation, military, and commercial aircraft. Figure 1-1, taken from U.S. General Accounting Office report GAO/RCED-94-15 (1993), summarizes accident statistics on general aviation operations in mountainous areas of the United States. Researchers found that the accident rate was nearly 40 percent higher in 11 western mountain states than in the other 37 continental states, and 155 percent higher for airports with towers located in mountainous areas, when compared with similar airports in nonmountainous areas. During the period from 1983 to 1992, 60 percent of the accidents at 5 selected nontowered, mountain airports were associated with weather-related factors, while 45 percent of accidents were associated with weather at 5 nontowered, nonmountain airports. One explanation for the higher risk associated with operations in mountainous areas was determined to be weather. The implication is that the combination of weather and mountainous terrain is particularly hazardous.

Air carrier and military aircraft also have been victims of mountain-induced high winds and associated turbulence. Table 2-1 depicts a partial list of accidents/incidents that have occurred during the period from

Table 2-1. Turbulence-related accidents and incidents occurring in the vicinity of mountains.

Event	Date	Location	Comments
Accident	31 Mar 93	Anchorage, AK	B-747 turbulence. Loss of engine.
Accident	22 Dec 92	West of Denver, CO	Loss of wing section and tail assembly (two-engine cargo plane). Lee waves present.
Accident	09 Dec 92	West of Denver, CO	DC-8 cargo plane. Loss of engine and wing tip. Lee waves present.
Unknown Cause; Accident	03 Mar 91	Colorado Springs, CO	B-737 crash.
Accident	12 Apr 90	Vacroy Island, Norway	DC-6 crash.
Severe Turbulence	24 Mar 88	Cimarron, NM	B-767 + 1.7 G. Mountain wave.
Severe Turbulence	22 Jan 85	Over Greenland	B-747 + 2.7G.
Severe Turbulence	24 Jan 84	West of Boulder, CO	Sabreliner, ~+0.4G, -0.4G.
Severe Turbulence	16 Jul 82	Norton, WY	DC-10, +1.6G, -0.6G.
Severe Turbulence	03 Nov 75	Calgary, Canada	DC-10, +1.6G.
Accident	02 Dec 68	Pedro Bay, AK	Fairchild F27B. Wind rotor suspected.
Accident	06 Aug 66	Falls City, NB	BAC 111. Wind rotor suspected.
Accident	05 Mar 66	Near Mt. Fuji, Japan	B-707. Wind rotor suspected.
Accident	01 Mar 64	Near Lake Tahoe, NV	Constellation. Strong lee wave.
Accident	10 Jan 64	East of Sangre de Cristo Range, CO	B-52. Wind rotor suspected.

January 1964 to March 1993. It is evident from these data that accidents or incidents associated with severe turbulence in mountainous areas are not limited to one locality or operating altitude, a particular time of year, or a specific type of aircraft. In many cases, other aircraft operating in the vicinity of the accident encountered only weak turbulence, suggesting that severe wind events can be highly localized, extremely violent, and short-lived. As has been shown to be the case for accidents caused by microbursts, mishaps associated with the most severe orographic (of or relating to mountains) wind events may represent a case of being at the wrong place at the wrong time. As with the microburst phenomenon, pilots need effective tools for detecting the presence of orographic strong winds and turbulence. They also need strategies for avoiding encounters with these potentially deadly phenomena and obtaining maximum aircraft performance in dealing with an in-flight confrontation.

The most severe orographic wind events usually occur when the large-scale (or, synoptic) winds are strongest, from late fall to early spring.

During the remainder of the year, when the synoptic winds are normally much weaker, hazardous winds in the vicinity of mountains are more likely to be associated with thunderstorms and their outflow fields.

3.0 THE EFFECTS OF OROGRAPHIC WINDS AND TURBULENCE ON AVIATION OPERATIONS

Orographic winds and turbulence affect all types of aircraft operations. As will be described below, regardless of the type of aircraft, operations near mountainous areas can be hazardous.

3.1 HIGH-ALTITUDE OPERATIONS

Turbine-powered aircraft operating at cruise altitudes above flight level (FL) 180 in the vicinity of mountainous terrain may encounter moderate or greater turbulence associated with orographic winds. This type of turbulence may be characterized by relatively rapid onset and can lead to structural damage or airframe failure. For example, during the winter of 1992 near Denver, Colorado, mountain-wave turbulence caused the separation of an engine from a DC-8 and loss of the outboard portion of one wing.

Structural damage is not the only danger associated with high-altitude turbulence encounters. It is possible to operate some turbine-powered aircraft at such weights and altitudes so that their cruise airspeed is only a few knots below the onset of Mach buffet and a like speed above stall buffet. In this situation (the so-called coffin corner), turbulent airspeed excursions of moderate or greater intensity (15 knots (kt) or more) can quickly lead to high-speed upset, Mach tuck, and loss of control. One method for avoiding an upset, if the turbulent area cannot be avoided, is to fly the aircraft at a lower cruise altitude and/or loading to a lower weight.

3.2 *TAKEOFF AND LANDING*

Takeoff and landing concerns include experiencing turbulent air with inadequate stall margins, loss of directional control on or near the runway, rolling moments that surpass aircraft roll authority, and downdraft velocities that exceed the climb capability of the aircraft, particularly for airplanes with high wing- and power-loading. It is important to realize that localized gusts in excess of 50 kt, with downdrafts greater than 1500 feet (ft) per minute, are not unusual. Instances of structural damage have occurred in such conditions; for example, on 31 March 1993, a B-747 experienced engine separation shortly after takeoff from Anchorage, Alaska.

Vortices spawned by the interaction of strong winds and high terrain can lead to severe turbulence and aircraft rolling moments that may exceed the pilot's ability to maintain aircraft control. Although more research is needed, there is evidence that moving vortices in the lee of mountains can markedly increase the likelihood of loss of control (NTSB, 1992).

3.3 *LOW-LEVEL MOUNTAIN FLYING*

Aircraft that engage in low-level flight operations over mountainous terrain in the presence of strong winds (20 kt or greater at ridge level) can expect to encounter moderate or greater turbulence, strong up- and downdrafts, and very strong rotor and shear zones. This is particularly true for general aviation aircraft. One such aircraft was involved in an accident on 22 December 1992, when a twin-engine cargo airplane crashed west of Denver, Colorado, in the presence of mountain waves.

The mountain flying literature cites 20 kt as the criterion for classifying a wind as "strong." As used in the current document, this criterion refers to the large-scale (or prevailing wind in the area as opposed to a local wind gust) wind speed at the crest of the ridge or level of the mountain peaks, upwind of the aircraft's position. Such an ambient wind flow perpendicular to a ridge will lead to substantially stronger surface winds, with the likelihood of turbulence. Similar wind enhancements can be anticipated near the slopes of an isolated peak. Forecast and actual wind speeds at ridge level can be determined from the FD (forecast winds and temperatures aloft) and UA (PIREPS) products, respectively. In contrast, downdrafts over forested areas may be strong enough to force aircraft down into the trees, even when the aircraft is flown at the best rate-of-climb speed. This effect on the aircraft is exacerbated by loss of aircraft performance because of the high-density altitude.

4.0 SOURCES OF MOUNTAIN-INDUCED WIND HAZARDS FOR AVIATION

4.1 A Review of Key Meteorological Concepts

As previously noted, the atmosphere is a fluid and its motions generally obey rather well-understood mathematical relationships describing fluid motion. Many atmospheric disturbances occur as periodic events; that is, they are waves, with a measurable wavelength, period, phase speed, and amplitude. The wave disturbances that develop in the atmosphere are a result of the interactions among a number of forces. These forces normally include pressure gradients, the Coriolis force, gravity, and friction.

Large-scale atmospheric waves (on the order of 1,000 nautical miles (nm)) exhibit primarily horizontal motion. The vertical motion in these waves is several orders of magnitude less than the horizontal motion. Examples of this type of wave are the synoptic- and planetary-scale waves found on constant pressure analyses (Figure 4-1). Other atmospheric waves, however, are smaller in horizontal scale.

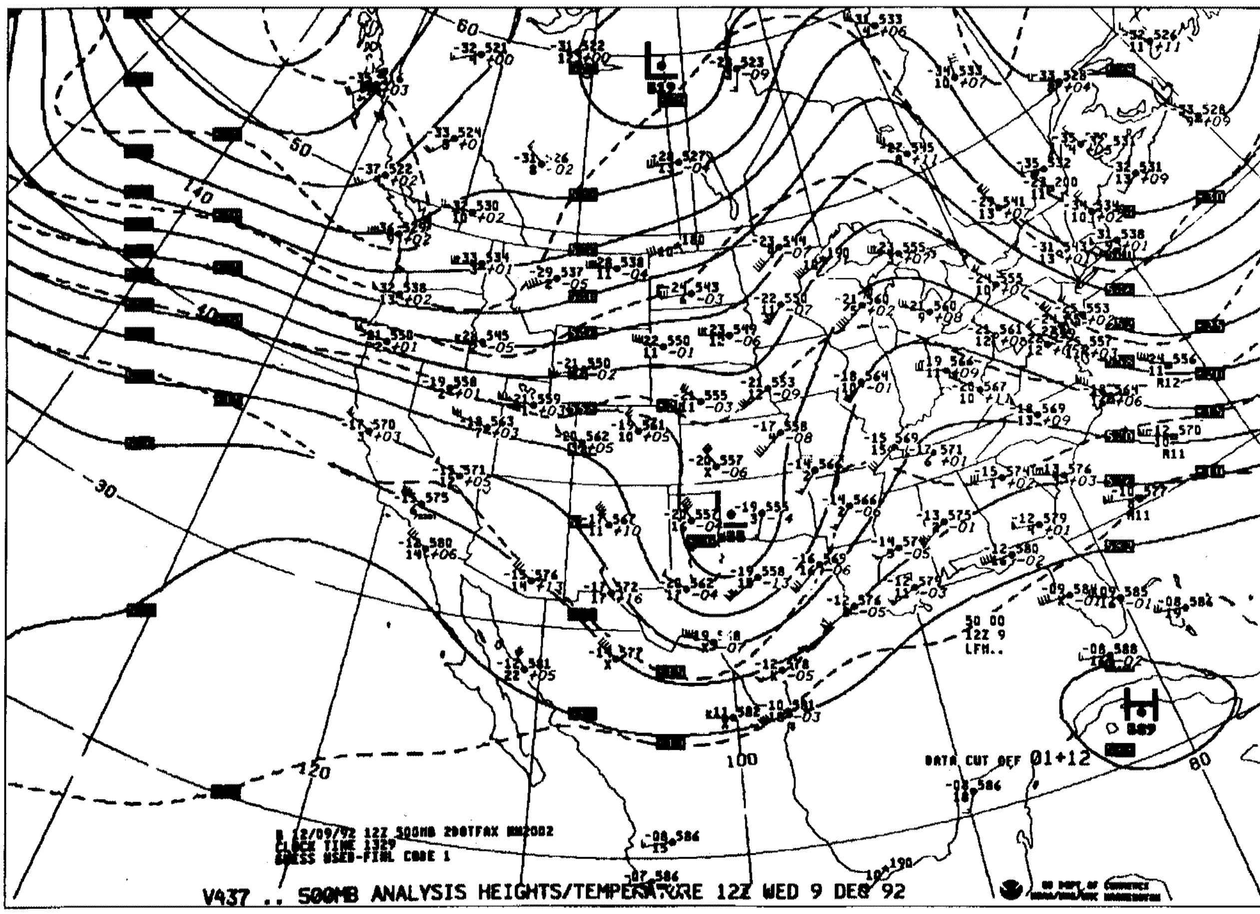


Figure 4-1. Example of a large-scale atmospheric wave pattern as seen on a National Weather Service constant pressure chart (500 mb). The solid lines are approximately parallel to the wind flow at this level. Rawinsonde observations are plotted. This example happens to be a few hours before a DC-8 experienced engine separation west of Denver, Colorado (see Table 2-1).

In these smaller horizontal scale waves, the ratio of the vertical motion to the horizontal motion is much greater than is the case for the large-scale waves. The most important waves exhibiting this property are gravity waves, so called because the restoring force is gravity, and shear-induced or Kelvin-Helmholtz (K-H) waves. A familiar example of a gravity wave is a wave on the ocean's surface. Atmospheric gravity waves also are very common, but are generally invisible unless clouds are present.

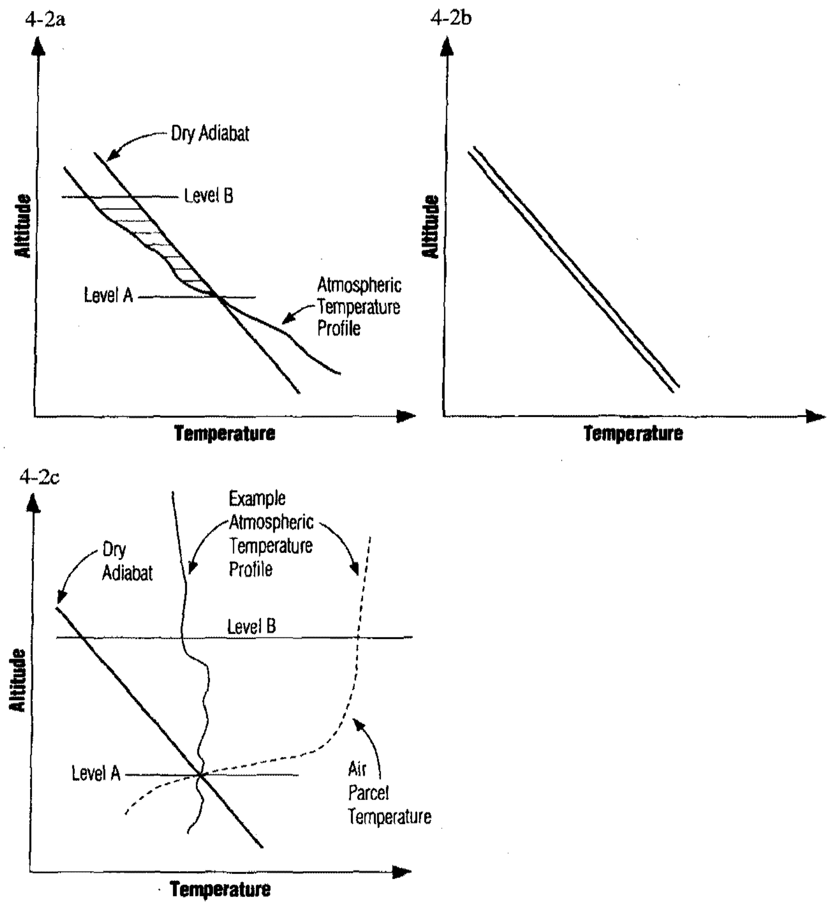
Mountain ranges can generate very strong, large amplitude gravity waves that can produce serious hazards to mountain flying. For that reason, we will consider their properties in some detail. In nonmountainous areas, shear-induced waves are a primary source of turbulence at altitude. In the vicinity of mountainous terrain, however, shear-induced waves can often be found superposed on larger-scale gravity waves, thus constituting an important source of turbulence.

4.2 A Review of Static Stability and Stable/Unstable Atmospheric Stratifications

Atmospheric stability describes the vertical distribution of air density over a given location and at a given time. If relatively heavy air overlies less dense air, the tendency will be for overturning and mixing to occur until a new, more stable atmospheric "mixture" (with less dense air above) results. In general, the more rapidly the atmosphere cools with height, the more unstable it is (and the less resistant to vertical motions). Conversely, an area of the atmosphere that warms with increasing altitude (an inversion) is quite stable and resistant to vertical motion.

The stability of the atmosphere is related to the vertical displacement of "parcels" of air. Vertically moving parcels of unsaturated air are cooled by expansion (if rising) and warmed by compression (if descending) at a fixed rate (the dry adiabatic lapse rate, 3 degrees Celsius/1,000 ft). A review of stability concepts is shown in Figure 4-2.

In order for gravity waves to develop, the atmosphere must possess at least some degree of static stability. This is because in an unstable atmosphere, an air parcel that experiences a vertical displacement (such unstable air being forced upward when it interacts with a mountain) will continue to rise, rather than be forced back down to its original level. A stable atmosphere tends to suppress vertical motions because atmospheric stability controls the motions resulting from vertical deflection of the atmosphere by terrain.



Figures 4-2a-c. Determination of atmospheric stability: (a) unstable case; (b) neutral case; (c) stable case.

Figure 4-2a shows an area of the atmosphere in which the temperature decreases rapidly with height (at a rate greater than the dry adiabatic lapse rate). In this case, the expansional cooling of a rising parcel moving between level (a) and level (b) takes place at a slower rate than that of the surrounding atmosphere. As a result, the parcel will be warmer, therefore less dense, than its surroundings at any level above its starting point, and it will continue to rise with no further outside lifting force required. This is an unstable atmosphere, one in which mountain waves generally cannot form because no oscillations will occur.

Figure 4-2b depicts a situation in which the atmosphere cools at exactly the same rate as a rising unsaturated parcel (the dry adiabatic lapse rate). As a result, the parcel always will be at the same temperature as its surroundings, and will be neutrally buoyant. This is a state of neutral stability; the rising parcel will have no propensity to either rise on its own or return to its original level, once the external source of lifting ceases.

Finally, Figure 4-2c also demonstrates how a large-scale atmosphere may cool less rapidly than the dry adiabatic lapse rate and may even warm with height. In this case, the rising unsaturated parcel always is colder and more dense than its surroundings due to the expansional cooling that it experiences. When the external lifting force ceases, the parcel of air that has been lifted will begin to descend back toward its original (equilibrium) level. The motion that results is a wave (a gravity wave), because the parcel will generally tend to overshoot its equilibrium level and undergo a period of oscillation, just as an airplane that has positive static and positive dynamic stability will oscillate in pitch about its trimmed altitude for a period when disturbed from trim. It is important to note that some degree of stability must be present in the atmosphere in order for wave motion to result from air being forced to rise over mountainous terrain.

4.2.1 Summary Comments on Stability

- The less rapidly the atmosphere cools with height, the more stable it is.
- Some degree of stability must be present in order for wave motion to develop in air being forced over a mountain.

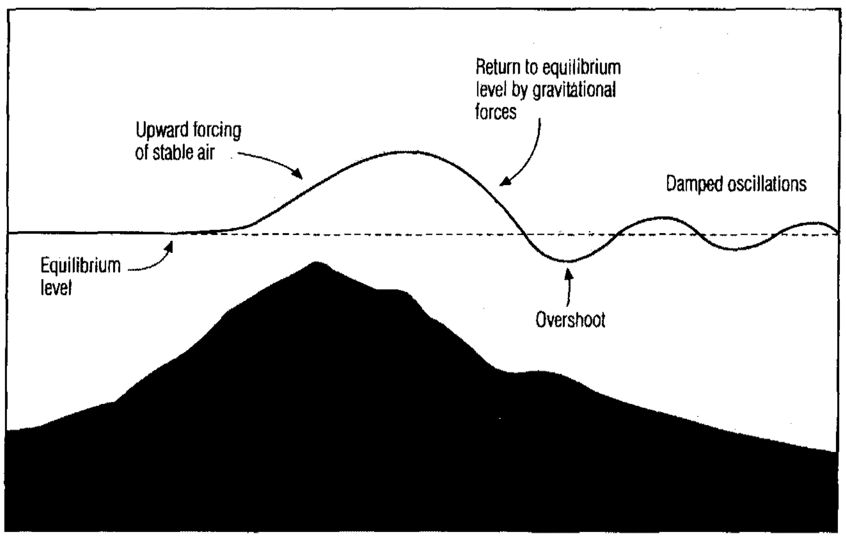


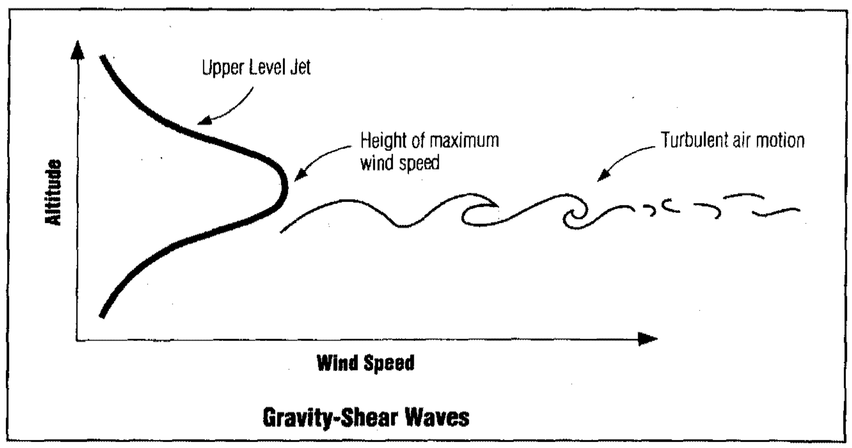
Figure 4-3. Oscillations associated with a gravity wave.

4.3 Elementary Theory of Gravity Waves and Shear-Induced Waves

As stable air is deflected vertically by an obstacle (for example, when an air mass moves over a mountain ridge), it resists the displacement because as it rises it is heavier than the air surrounding it and gravity is acting to return it to its equilibrium level. Because of its negative buoyancy, the deflected air begins to return to its original level once it has cleared the ridge. However (as noted in the previous section), its momentum will cause it to overshoot the original altitude, warming by compression and now becoming less dense than the surrounding air. As a result, it begins to rise back to the equilibrium altitude, overshoots once more, and continues through a period of oscillation before the resulting wave motion damps out. This process is depicted in Figure 4-3.

The described gravity wave will have measurable wavelength, amplitude, phase speed, and period. The period of this type of atmospheric disturbance is related to the temperature of the air and the "spread" between the existing lapse rate and the dry adiabatic lapse rate (or, equivalently, the

Figure 4-4. Growth and breakdown of waves included by vertical wind shear in a stable layer of the atmosphere.



degree of stability present). In general, the large-scale wind (wind shear) change in altitude and temperature (lapse rate), the size and shape of the mountain or ridge over which the air is moving, and the orientation of the wind relative to the ridge line all work together in determining the character of the disturbance that develops.

When wind shear is very strong, another type of wave is possible. These waves, called gravity-shear or Kelvin-Helmholtz (K-H) waves, can occur when the kinetic energy inherent in the shear can overcome the damping effects of a stable temperature lapse rate. This effect is illustrated in Figure 4-4. If the wind shear that penetrates the layer of atmosphere is weak (some wind shear is nearly always present), a shear-induced wave motion will not occur. However, if the magnitude of the wind shear exceeds a critical value, wave motions will begin spontaneously within the shear layer resulting in a K-H wave. The amplitude of the resulting wave will grow with the kinetic energy in the surrounding wind field until, like an ocean wave breaking on the shore, the wave overturns and breaks down into turbulence. The resulting turbulence can have a range of effects on aircraft. The clouds associated with shear-induced gravity waves can frequently be observed in the atmosphere, as shown in Figure 4-5a and Figure 4-5b.

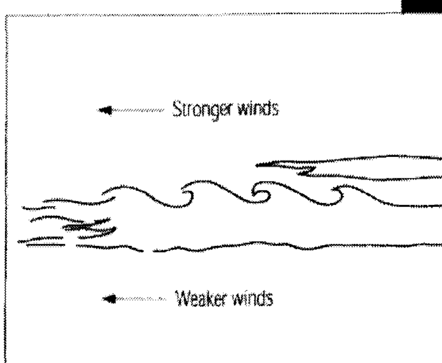


Figure 4-5b.


Figure 4-5. Clouds associated with Kelvin-Helmholtz waves over Laramie, Wyoming (photograph ©, B. Martner).

K-H waves are quite common in the atmosphere; they can form in the vicinity of thunderstorms, in shear layers near the jet stream, and in association with stable regions of the atmosphere that are topped by a strong wind shear layer (such as the top of a pool of cold air on the lee side of a mountain). In fact, K-H instability induced by the wind shear associated with strong winds aloft is likely the chief source of high-level turbulence away from mountain ranges (clear air turbulence, or CAT). The mechanism that causes this type of disturbance can be compared to that of a flag flapping in a breeze. The flapping is a result of instabilities created by the wind shear along the flexible surface of the flag, analogous to the wind shear through a very stable (but shallow) layer of the atmosphere.

4.3.1 Summary Comments on Gravity Waves and Shear-Induced Waves

- A parcel of air within a stable air mass moving over a mountain will undergo wave motion.
- The resulting wave is a gravity wave with up-and-down motions.
- Gravity waves can grow in amplitude until they "break" into turbulence.
- If the magnitude of wind shear exceeds a critical value, turbulence will occur.

4.4 Breaking Waves and Turbulence

As indicated in the previous section, waves frequently develop in areas of the atmosphere that are characterized by stable air that is in motion over terrain, and in areas where the direction and/or speed of the horizontal wind changes rapidly with increasing altitude (that is, locations with strong vertical shear of the horizontal wind). It is important to understand that these waves can be quite powerful, in terms of the vertical motions within the wave, while being relatively turbulence-free. In this case, updrafts and downdrafts can be strong enough to produce significant altitude excursions or, if altitude is maintained, large changes in indicated airspeed (at fixed power settings). In fact, for an aircraft at cruise, indications that a wave is being encountered may include pitch and trim changes (manual or autopilot) necessary to maintain altitude with corresponding changes in airspeed, even in the absence of accompanying turbulence. However, the air may be extremely rough, perhaps destructively so in zones of shear and rotation under the waves, or when shear-induced waves roll up and then break down into small-scale turbulence (Figure 4-5a-b).

The concerns for pilots operating in mountainous areas when winds are strong include the potential for loss of aircraft control and possible turbulence-induced structural damage to the aircraft.

Our purpose here is to provide information about the meteorological events that can occur, along with suggestions for determining the likelihood of their presence and relative strength by using commonly available reports and forecasts during pre-flight planning and visual indicators prior to takeoff and while airborne. We have identified two important atmospheric characteristics related to wave motion: air stability, and wind direction and speed. First, we need to know something about the overall stability of the air moving over the mountains. Second, we need a measure of the wind direction and speed at various altitudes near ridge level and above.

5.0 ATMOSPHERIC DISTURBANCES IN MOUNTAINOUS AREAS

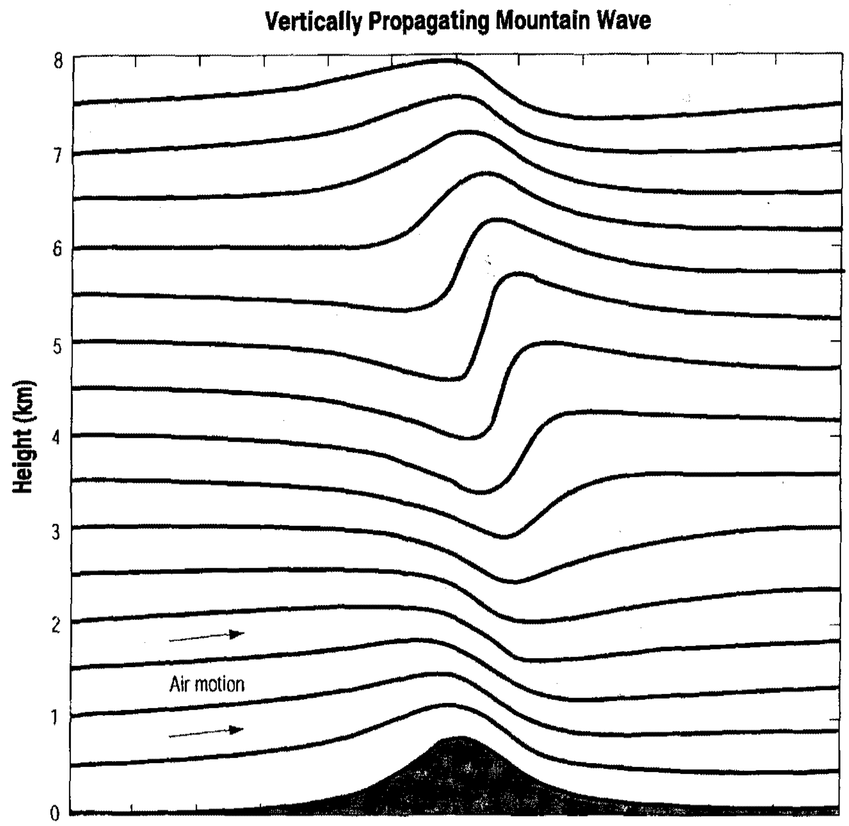
5.1 LARGER-SCALE HAZARDS

This section describes some of the most important types of waves that can develop in mountainous areas, the atmospheric environments in which they develop, and strategies for discerning their presence and avoiding them.

When the atmosphere encounters a mountainous barrier, a number of responses are possible. If the wind is weak or the moving air mass exceptionally dense, the mountains may act as a dam, preventing the motion of air over the barrier. More frequently, strong winds flow over or around mountains or ridges. If the surrounding atmosphere is unstable, the vertical displacement of the air will (if sufficient moisture is present) lead to thunderstorm formation or at least the development of deep convective clouds. However, if the wind is sufficiently strong and the surrounding atmosphere is stable, a wave will develop, as previously described.

The wave that results from vertical displacement of a stable air mass over a mountain or ridge can generally take one of two forms: vertically propagating mountain waves and trapped lee waves. Both types of waves can be hazardous to aviation operations. The particular type of wave or combination of waves that forms depends on the nature of the mountain range and on atmospheric properties upwind of the mountain. It is possible for both types of waves to exist at the same time, as will be seen in some of the pictures included in this AC. It also is possible to have hybrid or intermediate forms, that is, waves that are only partially trapped.

Figure 5-1. Schematic of a vertically propagating mountain wave (after Durran and Klemp, 1983).



Aircraft hazards associated with these features can range between extremes of no effect at all (for weak, laminar-flow waves) to potentially destructive turbulence (for large-amplitude breaking waves with strong rotor zones). The pilot's task is to be aware of the potential for wave development, assess its likely strength and location, and prepare for an encounter (reduce airspeed to turbulent air penetration speed, secure loose objects, etc.) or plan an appropriate diversion to avoid the area containing the disturbance.

5.1.1 Vertically Propagating Mountain Waves

Figure 5-1 shows a schematic of a vertically propagating mountain wave. This feature is essentially a standing gravity wave whose energy propagates vertically. For this class of wave, nothing is preventing vertical propagation, such as strong wind shear or neutrally stable atmospheric layers. Once again, the mere fact that a wave has developed in air moving over a mountain (or other barrier) does not in itself indicate problems for an aircraft operating in the vicinity. The potential for hazard is a function of the strength of the wave and whether or not an area of the wave "breaks" into turbulent motions that, in the extreme, can lead to structural damage or failure of an aircraft component.

With this type of wave feature, air that is moving nearly perpendicular to the barrier is deflected upward and accelerated as it passes over the crests and down the lee slopes of the terrain. Notice in Figure 5-1 that the standing wave has developed vertically above the mountain crest and that the resulting wave tilts upwind with height. This vertical propagation of the wave means that the effects of the mountain range can be felt at heights significantly above the actual altitude of the peaks (at times reaching in excess of 60,000 ft). As a result, aircraft flying at virtually any altitude may have to deal with significant turbulence and wave-induced altitude excursions. In fact, the amplitude of this type of wave actually increases with height above the mountain (in the absence of atmospheric features, such as strong inversions or shear layers, that would tend to partially reflect or absorb the upward-moving wave energy). This amplification is a consequence of the normal decrease in air density with altitude.

The amplitude of the wave will be larger, for the same upstream conditions, the higher the mountain range above the surrounding terrain. Although, even very modest terrain relief can cause appreciable wave activity under the proper conditions. Wave amplitude also will tend to be larger for stronger cross-mountain wind components at mountain-top level. However, the actual amplitude depends on complex relationships between upstream atmospheric wind and temperature profiles and the height and shape of the particular mountain range. As you might imagine, stronger flow across the mountain leads to a deeper wave, given the same atmospheric stability. However, the greater the background stability, the shallower the resulting wave, at fixed-wind speed.

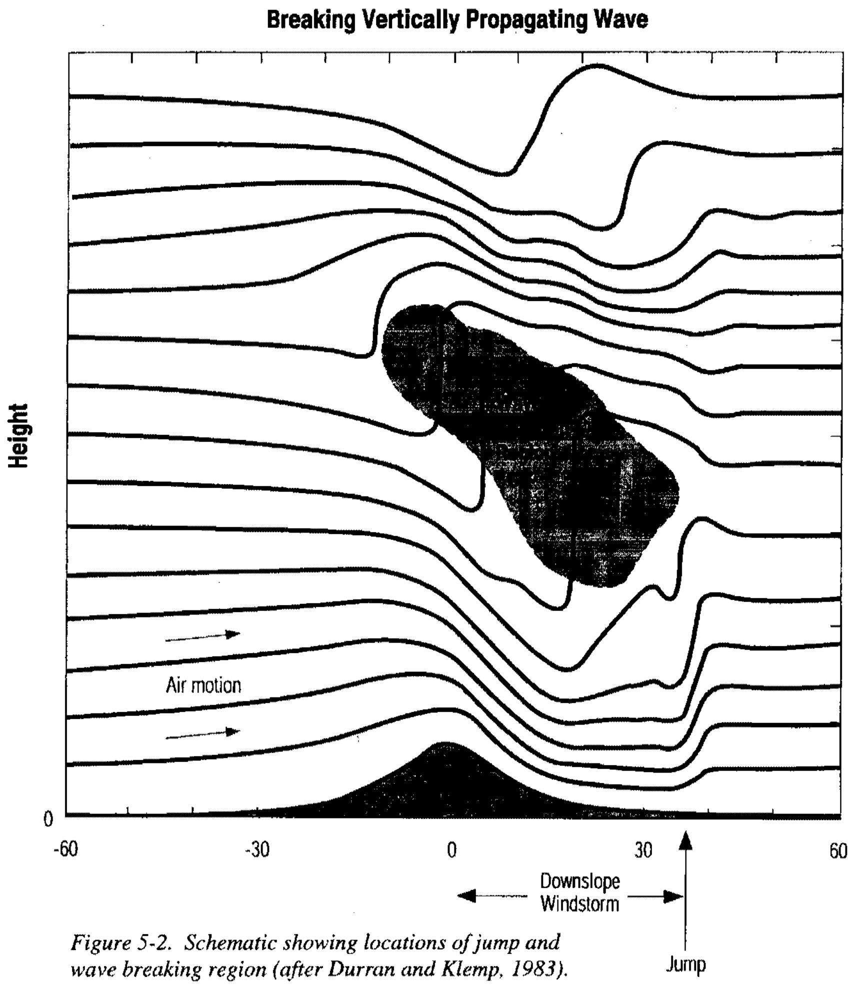


Figure 5-2. Schematic showing locations of jump and wave breaking region (after Durran and Klemp, 1983).

As we have noted, the primary concern for pilots with this type of feature is that the vertical motions of the air moving through the wave may become strong enough to "break" into turbulence. Such wave breaking is believed to have been the source of the turbulence encountered in the 9 December 1992 accident at FL310 west of Denver, Colorado (Table 2-1, and Ralph et al., 1994).

What do we mean by "wave breaking"? Looking again at the streamlines that show the airflow in Figure 5-1, we can see that high above the ridge there is a region of updraft. With a wave of modest amplitude (in which the vertical displacement of air moving through the wave is relatively limited), an aircraft flying through this region would likely experience appreciable "wave action," with altitude and/or airspeed fluctuations, but little turbulence. However, with sufficient amplitude, the wave breaks and localized updrafts and downdrafts occur. The consequences for a pilot flying through this region include airspeed and altitude deviations and the possible sudden onset of severe or extreme turbulence. This type of turbulence occurs typically between 20,000 ft and 39,000 ft msl and is therefore primarily of importance to turboprop and jet aircraft at cruise as they approach and overfly the mountain range.

Often accompanying these high altitude effects is the occurrence of very strong surface winds that result from the wave breaking aloft. In this case, strong downslope winds on the lee slopes can reach 100 kt in gusts, creating a low-level turbulence hazard for all aircraft. Further, these extremely strong low-level winds often abruptly terminate in a "jump" located some distance down the lee slope or well to the lee of the mountains themselves. These features are indicated schematically in Figure 5-2. The jump region is frequently an area of extreme turbulence extending to 10,000 ft or more above the surface. The area of the jump is sometimes marked by a line of ragged rotor clouds exhibiting very turbulent motion. Downwind of the jump, turbulence decreases in intensity but still may be quite strong.

Figure 5-3 depicts an intense mountain wave event that was investigated with aircraft, in which severe turbulence was encountered. The severe turbulence associated with this wave was widespread, occurring at high levels in and near the wave-breaking region and closer to the surface in the near vicinity of the jump.

Figure 5-4 shows a schematic of the jump feature, with a pronounced wave and associated strong shear layer. The shear layer (shown in the inset) is a source of the turbulence found with the jump.

Figure 5-5 is a photograph of the jump at the downstream edge of a region of strong downslope winds near Boulder, Colorado. In this picture, one can see the smooth, relatively laminar Foehn (wall) cloud below the much more ragged rotor cloud extending horizontally across the scene. The Foehn cloud is obscuring the mountains along the Continental Divide and is probably 3,000 to 6,000 ft thick. This feature is formed by condensation in the stable air that is being forced upward over the mountains. The area of the gap between this cloud and the overlying rotor cloud is a region of strong surface winds. The rotor cloud marks the downstream extent of this high wind, and probably the downstream limit of the strongest turbulence as well. We will have more to say later about rotor zones. For now, we can stress that the airspace near and below a rotor cloud frequently contains severe-to-extreme turbulence and definitely should be avoided.

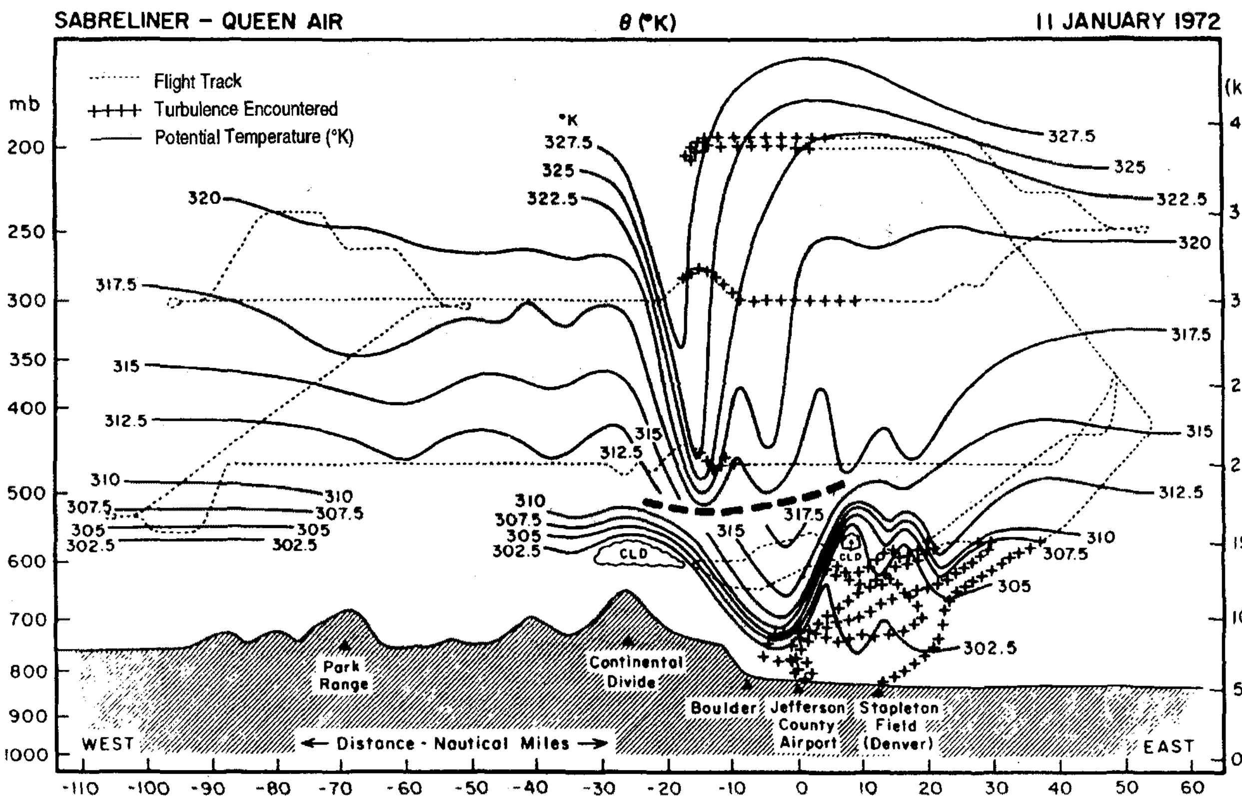


Figure 5-3. Aircraft flight tracks and turbulence encounters associated with a wave-induced high-wind event (taken from Lilly, 1978).

5.1.1.1 Forecast and Observed Data

What types of forecast and observed data are available for detecting the likelihood of vertically propagating waves? For forecast wind direction, wind speed, and vertical wind shear, look at the Forecast Winds and Temperatures Aloft (FD) at altitudes near ridge level (for example, 9,000, 12,000, and 18,000 ft for the western United States; and 3,000, 6,000, and 9,000 ft for the lower terrain in the eastern United States). As a guideline for the existence of operationally important vertically propagating waves, one normally finds a value of 1.6 or less for the ratio of wind speeds 6,000 ft above the ridge to those at ridge-top level. For example, vertically propagating waves would be a concern if the atmosphere is stable and the 18,000-ft winds are forecast to be 50 kt, while the forecast winds are 33 kt at 12,000 ft (ridge-top level in this example), a ratio of about 1.5.

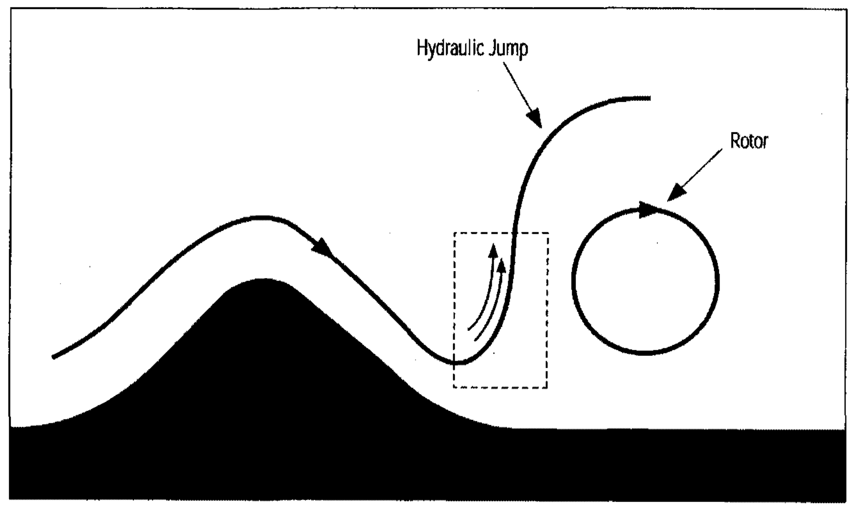


Figure 5-4. Schematic of the strong shear zone associated with a hydraulic jump in a mountain wave.

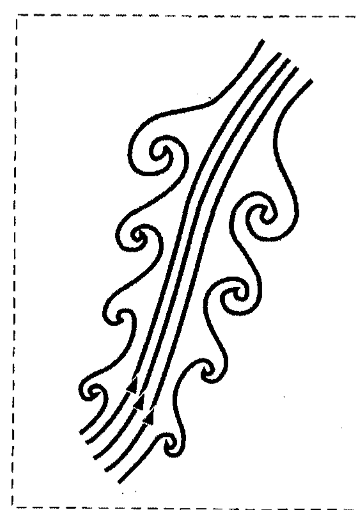


Figure 5-5. The Foehn cloud and rotor clouds associated with a jump at the downstream edge of a region of strong downslope winds near Boulder, Colorado (photograph ©, 1991, R. Holle).

One can apply this criterion to observed data as well, using the 700 mb and 500 mb constant pressure charts. Remember, however, that these observations are taken only twice daily, at 12Z and 00Z, so the data may be almost too old to be of value.

5.1.1.2 Charts

For a measure of the stability of the atmosphere, look at the stability chart (one panel of a four-panel facsimile chart called the Composite Moisture Analysis). The same caveat on data age applies to this information observed at the same time as the data on the constant pressure charts. Here, you are looking at the top numbers, the lifted indices, for a measure of the stability of the atmosphere. Positive numbers are stable, negative numbers are unstable; the larger the deviation from zero, the greater the stability or instability. You also can look at a radar summary chart; echoes characterized as thunderstorms, or RW+, are indicators of an unstable atmosphere. If you do not have access to these charts in person, you merely have to describe what you want to the Flight Service Station (FSS) briefer, who will read the data for you.

5.1.1.3 Other Assistance

Other important sources of information available during pre-flight planning include the Area Forecast (FA), AIRMETS and SIGMETS, Center Weather Advisories (CWA), Center Meteorological Impact Statements (MIS), and PIREPS. Indications of rotor clouds and/or altocumulus standing lenticulars (ACSL) in Aviation Routine Weather Reports (METARs) for an airport in or near a mountainous area are evidence that wave activity is present, as is a report of very strong surface winds in the absence of thunderstorms. It should be noted that automated observing systems are replacing human observers at many airports; therefore, cloud-type information may not be available.

Additional hints of the presence of gravity waves, available in METARs, include pressure changes and wind gusts. Pressure jumps are indicated as PRJMP, followed by amount and time of observation. A rapid rise or fall in pressure would be noted as PRESRR or PRESFR, respectively. Wind gusts in the absence of other obvious physical mechanisms (such as fronts) also can indicate a gravity wave.

Visible GOES (Geostationary Observational Environmental Satellite) imagery also can give an indication of the likely existence of a mountain-induced gravity wave. In this case, there will be indications of clouds that have a stationary upstream edge over or near the known location of a mountain range, with the orientation of this upwind edge generally parallel to the orientation of the range.

Accurately forecasting the strength of turbulence associated with a wave is much more difficult than predicting the likelihood of wave development. The occurrence of mountain waves depends on complex interrelationships of terrain and atmospheric structure; therefore, the simple "rules" cited above should be applied with caution.

5.1.1.4 Summary Comments on Vertically Propagating Mountain Waves

- Large-scale winds at ridge level, blowing perpendicular (or nearly so) to the ridge-line, are normally required.
- Wind speeds at ridge level are normally 20 kt or greater.
- Relatively weak vertical wind shear is present. Typically, the ratio of the wind speed 6,000 ft above ridge-top level to that at ridge-top level is less than 1.6 when this class of wave is of operational concern.
- The atmosphere is relatively stable. If there is a steep temperature lapse rate below 500 mb (an unstable atmosphere), with evidence of convection present, this type of atmospheric wave is unlikely to form.
- Vertically propagating waves are most likely and most intense during the winter and early spring months, when the winds at ridge level are strongest.
- In the generally prevailing westerly flow, these waves are most prevalent over mountain ranges that have a north-south orientation.
- Stronger ambient winds lead to a deeper wave.
- The greater the atmospheric stability, the shallower the wave (for a given wind speed).

5.1.2 Trapped Lee Waves

In the preceding section, we discussed an important type of mountain wave that propagates (i.e., transports its energy) vertically. Now we want to consider a second type of mountain wave, often manifested by a train of altocumulus standing lenticular (ACSL) clouds extending far downwind of the mountain (although trapped lee waves frequently occur without clouds). These waves are of concern for takeoff and landing operations and en route flight below FL250. The associated lenticular (lens- or airfoil-shaped) clouds may appear turbulent or smooth and, depending on the moisture stratification upwind of the mountain, multilayered. They are evident as relatively straight lines or bands of cloud (with clear spaces between), parallel to the mountain range but downstream from it.

The waves that produce these cloud features often are referred to as "trapped lee waves," because the wave energy is confined below a certain altitude. The mechanism confining this energy is strong wind shear above ridge level. Trapped lee waves are most likely to occur when the wind crosses a narrow mountain range, with a layer close to ridge level and upstream of the mountain that has strongly increasing wind speed with height and high stability, capped by a layer of strong flow and low stability.

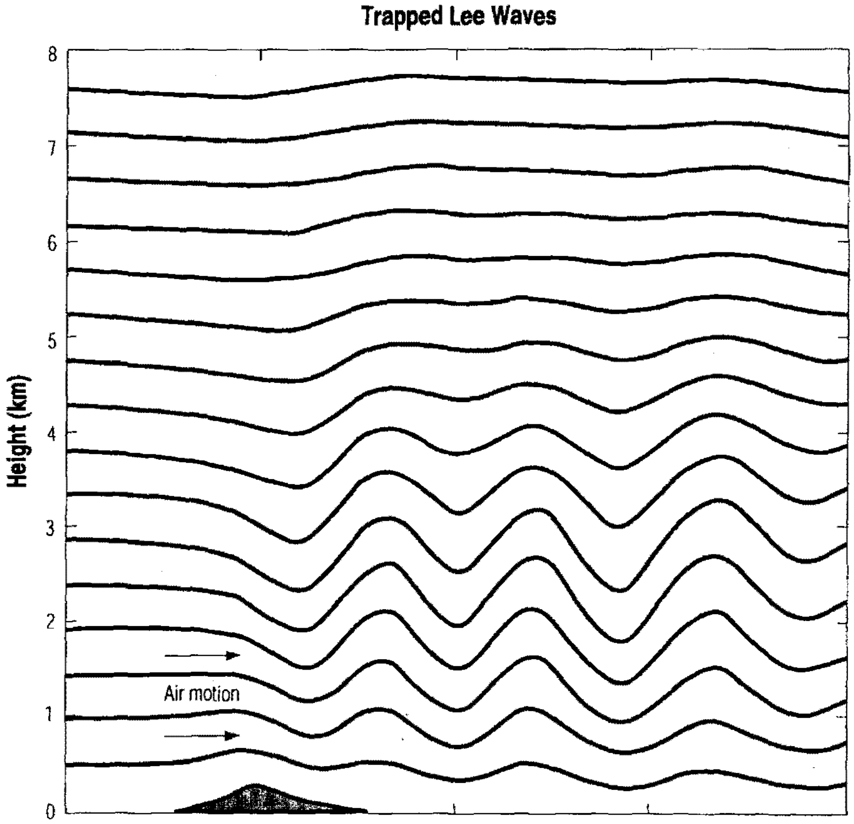


Figure 5-6. Computer simulation of trapped lee waves behind a 300-meter-high mountain.

Figure 5-6 depicts a trapped lee wave. Notice that this type of wave extends downwind from the mountain, does not develop to a high altitude, and has no upstream tilt, in contrast to the vertically propagating wave in Figure 5-1.

This class of wave presents less turbulence hazard at high altitude than do breaking vertically propagating waves, because the wave amplitude decreases with height within the "trapping layer," typically based within a few thousand feet of the ridge crest. As a result, these waves do not extend to as great an altitude. (An exception to this rule is when the atmospheric structure permits only partial trapping. This commonly occurs because the layer of wind shear that is instrumental in the trapping is weaker or shallower than necessary to do the job completely.)

However, at lower altitudes, trapped lee waves can create strong turbulence encounters for aircraft. Below lenticular clouds, the wind can be quite variable and gusty, although usually not extremely strong. The gusty winds can extend from the surface up to the base of the clouds, particularly during daylight hours of spring and summer when the sky is otherwise mostly cloud-free.

Cloud bases associated with trapped lee waves are typically one to several thousand feet above ridge level, and pilot reports in the vicinity frequently indicate moderate-to-severe turbulence beneath the clouds. The turbulence associated with trapped lee waves is related to the large horizontal and vertical wind shears below cloud level.

With this type of wave, there is frequently a strong shear layer near cloud base immediately to the lee of the mountain range. This separates a turbulent wake region below mountain-top level from the faster-moving, cloud-bearing air above. In the cloud layer itself, conditions typically range from turbulent near cloud base to smooth near cloud top. The clouds themselves give some indication of the degree of turbulence within them; smooth, laminar-looking edges and tops are associated with little or no turbulence, while a lumpy, non-uniform appearance and a visual impression of rolling motion about an axis parallel to the cloud is indicative of turbulence.

Superimposed on the smaller-scale turbulent motions that may be present are larger-scale up- and downdraft motions that are a part of the wave. Vertical shear of the horizontal wind is locally enhanced at the crests and troughs of the wave as a result of vertical transport (by the wave) of strong winds, leading to shear-induced turbulence.

Figure 5-7 shows lenticular clouds associated with a trapped lee wave. Note the laminar appearance of the flow within the cloud that has developed from expansional cooling and condensation of water vapor in the upward-moving portion of the wave.

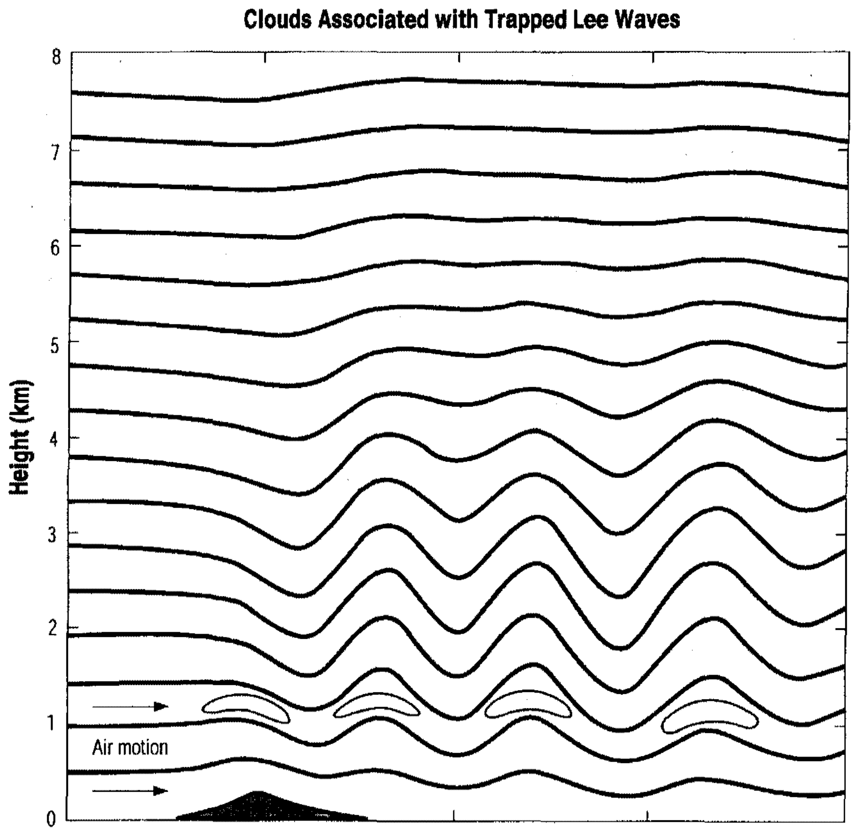


Figure 5-7. Lenticular clouds associated with a trapped lee wave (after Durran and Klemp).

Figure 5-8 depicts a striking example of clouds associated with a trapped lee wave. The rolling motions in these clouds are repetitive downstream, each cloud band corresponding to a wave crest. The bottom bright band of clouds is a Foehn wall on the mountains. Note the gaps in successive cloud bands. Although still pictures cannot show rotation within the clouds, time-lapse photographs of such cloud bands usually reveal a marked rolling motion, with descent on the downwind side of the band, ascent on the upwind side. Vertical motions measured by research aircraft in trapped lee wave clouds are typically 2 to 10 kt.

The cloud gap below the uppermost wave cloud in Figure 5-8 reveals some cirrus clouds that may be associated with a vertically propagating wave, which coexists with this trapped lee wave (not an unusual occurrence). When the trapped lee waves are evident as several regular cloud bands beginning immediately downwind from the mountain ridge as in Figures 5-7 and 5-8, any coexisting vertically propagating wave usually is not hazardous.

Figure 5-8. Clouds associated with a trapped lee wave (photograph ©, 1988, R. Holle).

5.1.2.1 Forecast and Observed Data

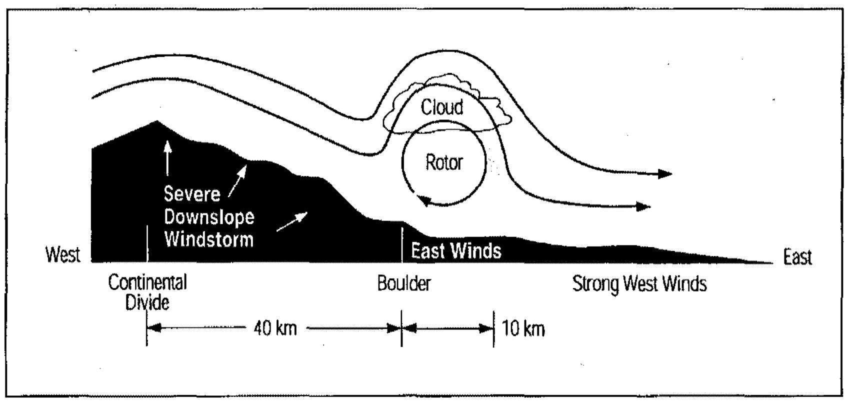
Determination of the likelihood of trapped lee waves should be made using the same forecast and observed data as for vertically propagating waves. Both are favored by stability in the lowest several thousand feet above the level of the mountain top. If this condition is met, then the simplest procedure available is to examine the vertical wind shear. For a given strength of wind at 12,000 ft, a strong increase in wind speed between 12,000 and 18,000 ft (at least a doubling is typical for trapped waves) with no dramatic change in direction indicates the likelihood that trapped lee waves will be the principal source of turbulence. On the other hand, only a small increase in speed in the wind component across the mountain range between 12,000 and 18,000 ft should be cause for concern that breaking vertically propagating waves will occur, particularly for high mountain ranges and very strong (25 to 30 kt or more) ambient winds at ridge-top level.

From a practical standpoint, the forecast of wave activity and reports of lenticular and/or rotor clouds, along with pilot reports of turbulence in the vicinity of the ridges, are sufficient for the assumption that wave activity is occurring. However, when flying early in the day or late at night, the absence of pilot reports may not be an assurance that no turbulence is present; similarly, the absence of clouds may mean only that the air is too dry for clouds to form. Therefore, in all cases, the forecast and/or measurement of ambient winds near ridge level of 20 kt or greater should cause pilots to assume that wave activity is present and make appropriate changes in takeoff/landing times, choice of departure or arrival airports, and en route course, unless reliable data indicate that there is no danger of a strong wave event. As is always the case in flight operations, the go/no-go decision should take into account the performance capabilities of the aircraft and the currency and experience level of the pilot.

5.1.2.2 Summary Comments on Trapped Lee Waves

- Trapped lee waves do not propagate vertically because of the capping effects of strong wind shear or low stability above.
- Aircraft turbulence encounters related to trapped lee waves are generally restricted to lower altitudes, whereas vertically propagating waves can affect all altitudes.
- Strong turbulence can develop near the bases of accompanying lenticular clouds, although such clouds may not be present.
- Forecasts of winds 20 kt or greater at ridge level should alert pilots to the likelihood of wave activity.

Figure 5-9. Conceptual view of a mountain lee wave rotor zone (1993, A.J. Bedard, Jr.).



5.1.3 Persistent Horizontal Roll Vortices (Rotors)

When mountain waves are present, it is quite common for a rotor zone to develop near or below ridge level on the downwind side of the mountain, under a wave crest and associated lenticular cloud (if sufficient moisture is present). This is an area of potentially severe-to-extreme wind shear and turbulence.

Figure 5-9 shows a schematic of the wind flow associated with this feature. As illustrated in this schematic, rotors typically mark the downwind terminus of a downslope windstorm. When this is the case, the rotor is really part of the "jump" discussed in Section 5.1.1. Although strong rotation is typically present within the rotor zone and associated cloud, a pilot in a moving aircraft may not be able to detect such motion visually until the aircraft is quite close to the vortex. In fact, from a distance, a rotor cloud may look like a rather innocuous cumulus cloud; however, the downwind side of the rotor cloud will typically be rounded in the direction of rotation of the rotor, with cloud tags or streamers at the bottom of the cloud mass. The latter features appear to be rapidly forming and dissipating, thereby giving some sense of rotation within the cloud.

Figure 5-10 is a photograph of a wave cloud and associated rotor cloud viewed from aloft. Noteworthy in this picture are the stacked lenticular clouds, which indicate that wave activity is occurring and point to the likelihood that the rather innocent-looking, rounded cloud below is indeed a rotor cloud.

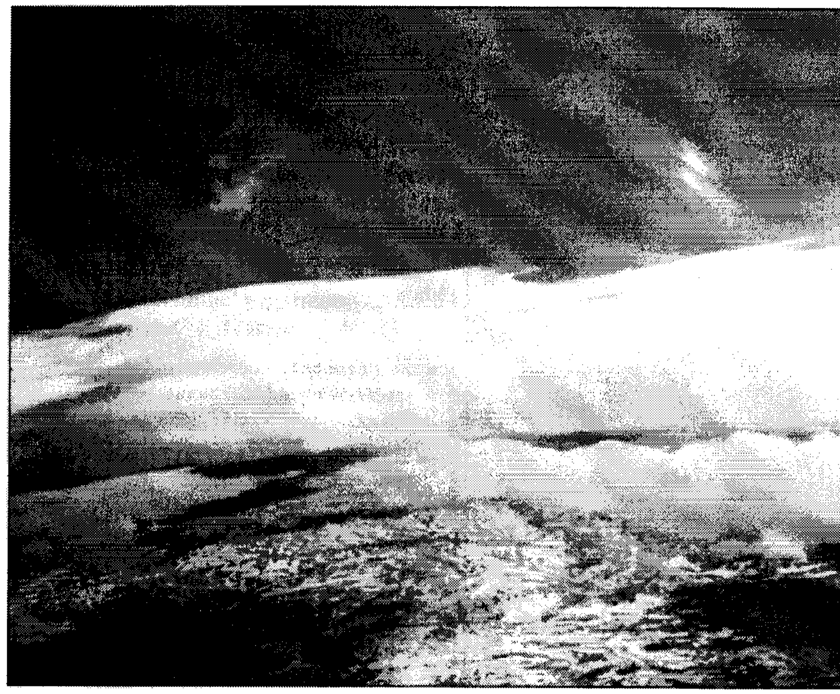


Figure 5-10. View from aloft of a wave cloud and associated rotor (photograph ©, NCAR).

Because of their potential for causing turbulence and loss of aircraft control, rotor zones should be avoided. Doppler lidar measurements in rotors have documented rotational speeds greater than 20 kt. Rotor zones are of concern not only because of the likelihood of strong turbulence in their vicinity (particularly on the upwind side of the rotor), but also because of the potential for rolling moments that could exceed the roll authority of the aircraft or otherwise lead to loss of control. Rotors are especially dangerous at low altitudes, particularly during takeoff and landing, when the aircraft is slowed and in a relatively high-drag configuration. As previously noted, there is evidence that translating rotors (moving vortices), with or without clouds, may be especially dangerous in causing aircraft upset and loss of control.

Since rotor zones can be a product of either type of mountain wave, the previously discussed forecast and observed data and the associated rules also can be applied in forecasting the likelihood of rotor zones. When waves are present, one should assume that a rotor zone exists below ridge level and within about 20 nm of the ridge. Pilots should be particularly cautious when they know or suspect that breaking vertically propagating waves or a downslope windstorm are occurring. Under these conditions, the rotor or jump zone will very likely be a location of severe-to-extreme turbulence and, in addition to horizontal axis vortices, may also contain vertical axis vortices of great intensity.

5.1.3.1 Summary Comments on Horizontal Roll Vortices

- Rotor zones can develop below ridge level downwind of a mountain in association with waves.
- In flight, rotor clouds may appear to be "normal" cumulus clouds.
- Rotor clouds may have strong turbulence and can produce large aircraft rolling moments, which can lead to loss of aircraft control.
- Translating rotors can be especially hazardous, because the combination of their rolling moments and translation speed can exceed aircraft roll authority.
- When waves are present, assume rotors exist below ridge level within 20 nm of the ridges.

5.1.4 Kelvin-Helmholtz Waves

As noted in Section 4.3, another type of wave can be found in a stable atmosphere within a region that has very strong vertical shear of the (large-scale) horizontal wind through a concentrated layer. Figures 4-5, 5-11, and 5-12 show clouds associated with such Kelvin-Helmholtz (K-H) waves. Figures 5-11 and 5-12 are more typical of cloud forms observed with K-H waves.

When K-H waves develop, eddies form within the shear zone and move with the background wind flow. In Figures 4-5, 5-11, and 5-12, the K-H waves cause localized changes in a larger cloud that is the visible manifestation of a mountain wave. The larger-size mountain waves (in the cases shown in these pictures, probably vertically propagating waves) contribute to locally increased vertical shear so that the wind above the cloud top is stronger than the wind below. The K-H waves are feeding on this difference in wind speed (wind shear). Thus, the existence of even small amplitude mountain waves increases the likelihood of encountering shear-generated turbulence. Often with this type of disturbance, there may be insufficient moisture for clouds to form, making the turbulent layer invisible but no less bumpy.

Although gravity-shear waves are typically not associated with the magnitude of aircraft hazard represented by the mountain waves that we have previously discussed, they are a frequent contributor to turbulence at altitude and are occasionally associated with aircraft reports of moderate-to-severe turbulence (Bedard et al., 1986). For purposes of our discussion here, the presence of clouds like those in Figures 4-5, 5-11, and 5-12 should alert pilots to anticipate at least some degree of turbulence in their vicinity.

In general, the stronger the wind shear associated with K-H waves, the stronger the disturbance that develops at the shear interface. Since this effect usually occurs within a fairly shallow zone, a modest altitude change (normally several thousand feet) should allow aircraft to clear the turbulence.

Figure 5-11. Clouds associated with gravity-shear (Kelvin-Helmholtz) waves (photograph ©, 1985, P. Neiman).

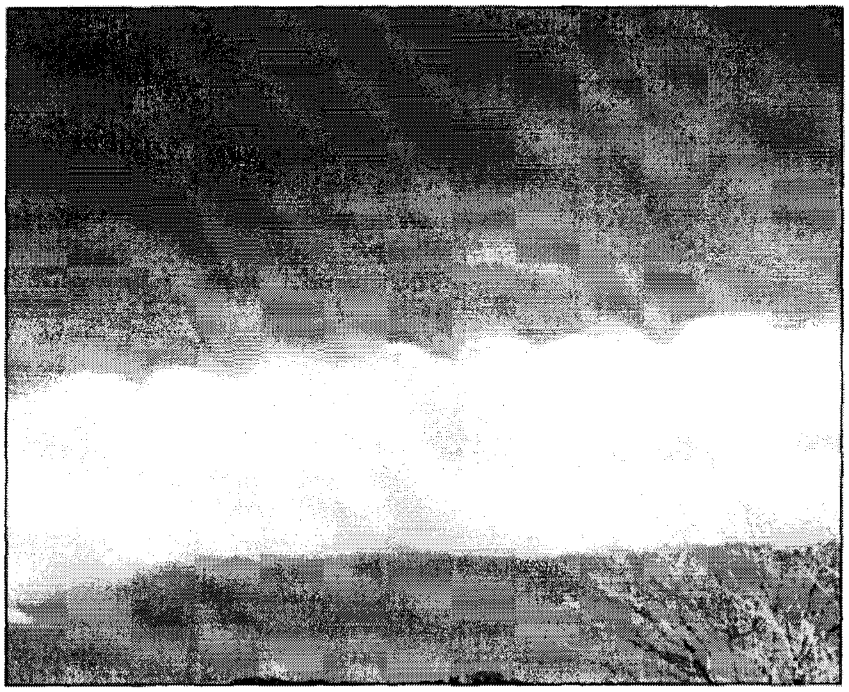


Figure 5-12. Clouds associated with gravity-shear (Kelvin-Helmholtz) waves (photograph ©, 1990, A.J. Bedard, Jr.).

5.1.4.1 Summary Comments on Kelvin-Helmholtz Waves

- Kelvin-Helmholtz waves occur in a stable atmosphere, with very strong vertical shear of the horizontal wind.
- These waves can lead to moderate or greater turbulence.
- Change altitude (normally, climb) to clear the turbulent zone, which is usually localized near the height of greatest wind shear.

5.2 Smaller-Scale Hazards

The following smaller-scale phenomena represent specific weather hazards for aircraft operating near mountains. These are intense disturbances that may or may not be associated with mountain waves. The origins and structure of some of these disturbances are speculative and also a subject of ongoing and proposed future research, both in the laboratory and through use of computer simulation. It is anticipated that this research plus future intensive efforts to obtain high-quality observations of these phenomena will greatly reduce the risk of deadly encounters with them.

5.2.1 Lee-Side Inversion With Shear Flow (Mountain-Induced Shear With No Wave Development)

Occasionally, an extremely strong low-level temperature inversion can occur in mountainous areas, with the inversion top below ridge level (perhaps 900-1,000 ft AGL) and a pool of very cold air at the surface. If this phenomenon occurs with strong wind flow above the inversion layer, there will be a concentrated shear zone near the inversion, which can lead to both significant turbulence encounters (caused by K-H instability) and abrupt airspeed changes for aircraft that penetrate the inversion on climbout or during descent. This situation is true particularly when significant mountain wave activity is present above the inversion in the strong flow aloft. In this case, the surface-based pool of cold air and the inversion above it shelter the surface from what might otherwise be a damaging windstorm.

Figure 5-13 is a dramatic view of a frontal boundary (made visible by high humidity in the cold air surge) advancing upslope. Above and ahead of the frontal boundary and inversion, winds are briskly downslope; the curl at the leading edge of the outflow in this picture indicates the formation of strong, shear-induced turbulence.

Figure 5-13a. A developing upslope flow associated with an approaching cold frontal boundary (photograph ©, 1990, A.J. Bedard, Jr.).

The process depicted in Figures 5-13a and 5-13b is shown schematically in Figure 5-13c, as the cold-air surge deepens. It should be noted that there may not be sufficient moisture present to produce such a vivid picture. Nevertheless, the presence of a strong inversion often is revealed by haze or pollutants trapped beneath it.

5.2.1.1 Summary Comments on Lee-Side Inversions with Shear

- A concentrated shear zone and turbulence can develop in the stable air associated with a temperature inversion when strong vertical shear is present above the inversion.
- This condition can cause abrupt airspeed changes for aircraft as they climb or descend through the inversion layer.

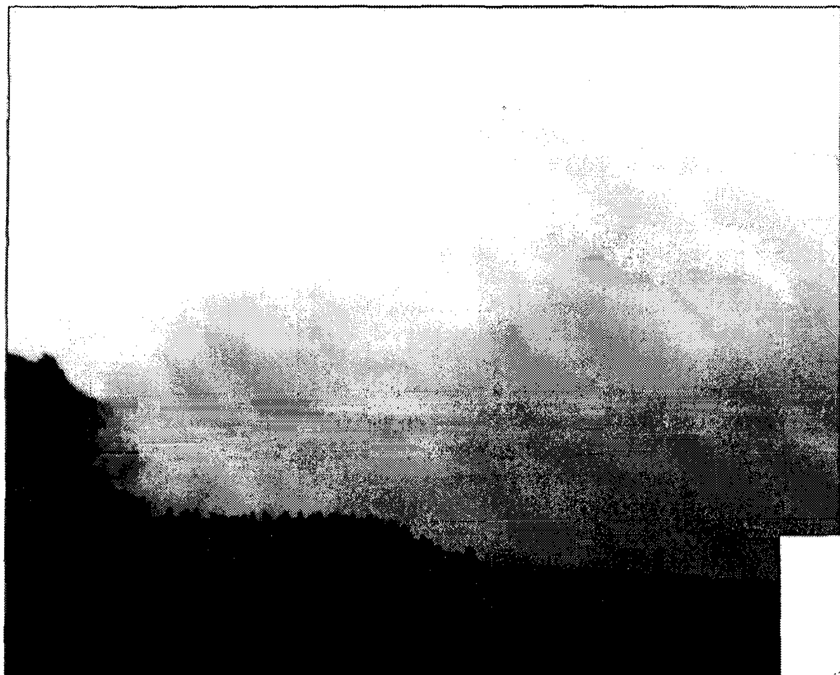


Figure 5-13b.

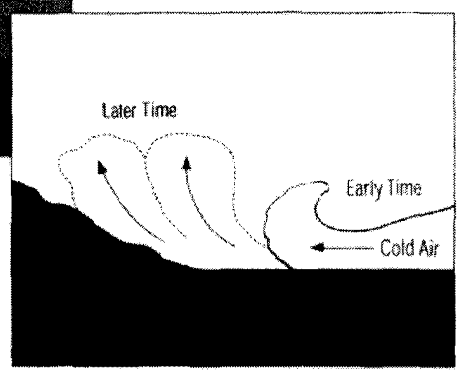


Figure 5-13c.

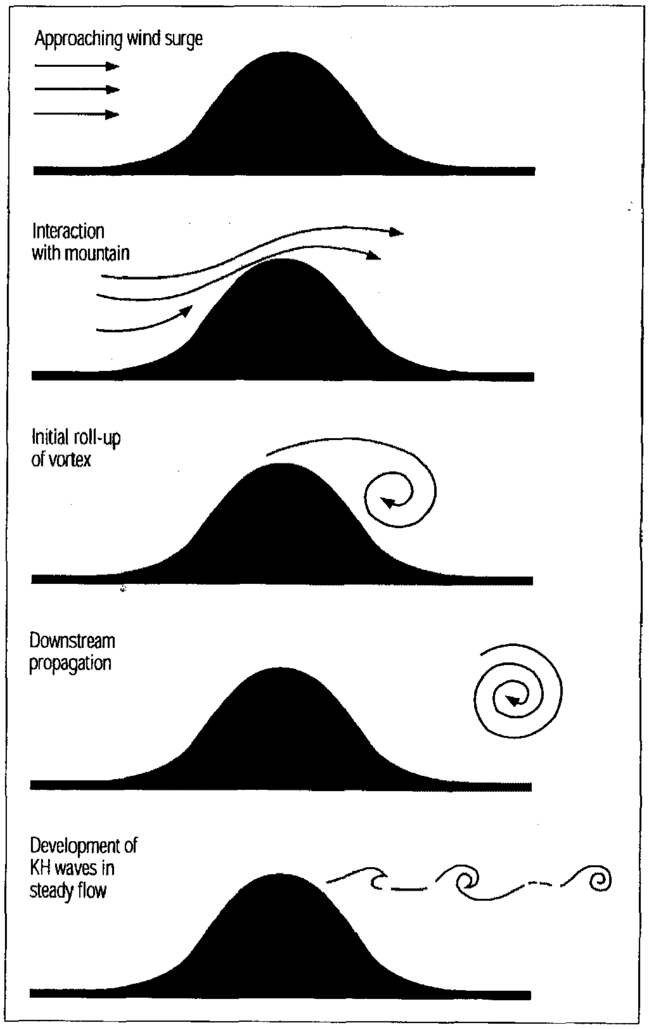
5.2.2 Non-Steady Horizontal Roll Vortices (Moving Horizontal Vortices)

The disturbances that we have been discussing up to this point occur in relatively steady flow regimes, that is, with no appreciable pulsations in the large-scale wind. We now turn to a type of disturbance that is poorly understood and potentially dangerous for flight operations, particularly while maneuvering for landing or during initial climbout. Doppler lidar measurements have shown that small-scale pulsations in the wind flow can occur during severe downslope windstorms (Neiman et al., 1988).

Laboratory studies suggest that a surge of wind across a ridge can initiate a vortex downwind of the ridge. Figure 5-14 shows schematically the development of such a vortex as a wind surge interacts with the mountain or ridge line. The vortex rolls up to maximum strength of rotation as it continues to move downwind away from the ridge and slowly dissipates. In its wake, with a return to steady flow, K-H waves develop at the top of the shear layer.

Extreme gustiness is a well-known characteristic of the surface winds during severe downslope windstorms. The origin of these gusts appears to lie in the wave-breaking process discussed in Section 4.4 (Clark and Farley, 1984; Clark et al., 1994). These gusts have been observed as repetitive surges of stronger airflow, using Doppler lidar techniques (Neiman et al., 1988). The interaction of such gusts with strong large-scale winds moving perpendicular to a ridge is a possible source of strong horizontal vortices of small scale. The greatest chance for small-scale horizontal vortices associated with breaking vertically propagating waves and windstorms would seem to be when wind surges interact with foothill terrain downwind of the main topographic feature that is causing the vertically propagating waves. We want to emphasize, however, that our understanding of the frequency of occurrence and causes of strong horizontal axis vortices is currently quite limited.

Figure 5-14. Development of a strong roll vortex associated with a wind surge down the lee slope of a mountain (1993, A.J. Bedard, Jr.).



Flight operations may be conducted in the vicinity of strong horizontal vortices without any encounters because they are highly localized, short-lived, and generally cloud-free. Conversely, one or more aircraft may encounter a strong, but invisible, vortex (that might be described as being like a "horizontal tornado," even though it is not) and undergo rolling moments and localized turbulence that make it impossible for the pilot to maintain aircraft control. Flight simulator results indicate that the danger from a traveling vortex is greater because of the additive effects of the speed of translation of the event and the rotation of the vortex (NTSB, 1992). That is, while the rotational strength of the roll itself may be within the control limits of the aircraft, the horizontal motion of the roll away from the ridge that spawned it appears to add a velocity component that may exceed the control authority of the aircraft, and the aircraft may roll or pitch past vertical. If this occurs at a low altitude, recovery may be difficult or impossible. More research is needed concerning translating vortex flows and aircraft response during interactions with these disturbances.

The possibility of encountering a horizontal axis vortex when flying in an area where breaking vertically propagating waves are suspected or anticipated should cause pilots to exercise extra caution during pre-flight planning or when approaching such an area. Our current lack of understanding of these disturbances prevents forecasters from issuing a general warning that hazardous horizontal-axis vortices will be a factor at a given airport, on a specific day, at a specific time. For now, the best advice is to be alert for the possibility of this strong vortex flow while operating at airports within about 20 nm of rough terrain, when low-level winds are strong and gusty. Blowing dust or other indications of strong wind, with any rolling motion present in the air near the ground, should lead one to consider delaying a landing approach or takeoff. Specific aircraft response techniques are beyond the scope of this AC and are a focal point of future research.

Figure 5-15. Strong horizontal vortex (photograph ©, 1984, E. Richter).

Figure 5-15 suggests a form that horizontal vortices can take. It is likely that such a cloud is the result of condensation taking place in the low pressure region of a vortex core. This cloud form is similar to the visible wingtip vortices of a landing aircraft that is flying in nearly saturated air. Such cloud forms should be avoided.

5.2.2.1 Summary Comments on Moving Horizontal Vortices

- Roll vortices can develop in nonsteady wind flow over a mountain ridge.
- The roll vortices develop and move downwind from the mountain.
- These roll vortices will occur in a generally turbulent environment.
- Aircraft encounters can lead to locally severe turbulence and strong rolling moments.
- Traveling vortices may present a greater hazard for aircraft because of the added velocity components.
- Pilots should watch for blowing dust, snow, and debris at the surface.

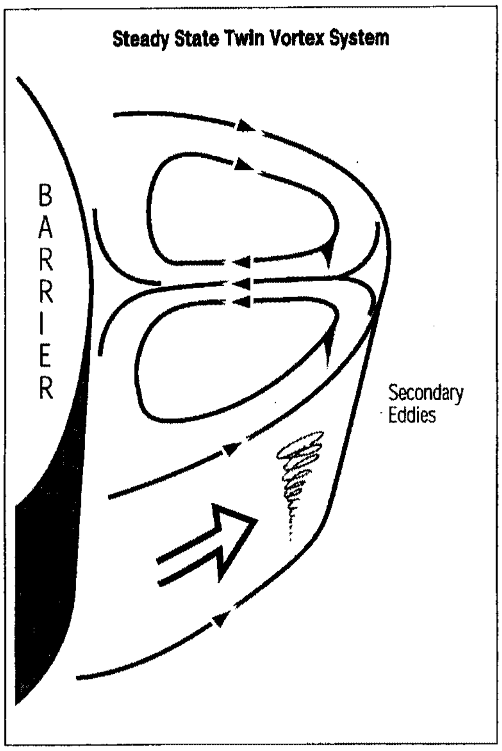


Figure 5-16. Schematic of vertically oriented vortices generated in the lee of an isolated mountain peak.

5.2.3 Intense Vertical-Axis Vortices

Analogous to the horizontal vortices described in the previous section are vertically oriented vortices of great intensity. Such disturbances have been documented (Zipser and Bedard (1982) and Bedard (1990)). As with horizontal-axis vortices, the origins of these vertical-axis vortices are uncertain. Circumstantial evidence suggests that they also are a likely consequence of wave breaking (see Section 4.4) and may be more likely downstream of localized rugged terrain (Bedard, 1993). Although they also may occur downwind of isolated peaks, as schematically illustrated in Figure 5-16, examples of such occurrences are not well-documented.

These vortices are not associated with thunderstorms and are therefore not tornadoes, but their wind speeds can reach 150 kt or more. An aircraft that inadvertently encounters such a strong vertically oriented vortex would most likely be subjected to severe airspeed excursions and associated G-loading. There have been cases in which a high-wind event has produced many of these strong, short-lived tornado-like vortices (Zipser and Bedard, 1982; Bedard, 1990). As is the case with horizontal vortices, there may be no visual indications of the presence of such a strong vertically oriented vortex—certainly no visible cloud.

Accurate forecasting of place and time of onset is similarly difficult or impossible. Probably the only reliable indicator of its presence is a swirling motion of trees, dust, and debris on the surface. Until arrays of wind measurement equipment such as profilers and Doppler lidars become more widespread near airports, such disturbances should be anticipated when operating in the lee of isolated mountain peaks in the presence of moderate or stronger winds.

5.2.3.1 Summary Comments on Vertical-Axis Mountain Vortices

- A strong wind surge around an isolated peak can produce secondary vertical-axis vortices that can reach tornadic intensity.
- There may be no visible cloud associated with these very strong vortices.
- Pilots should be alert for swirling motion of trees or surface debris, particularly when operating downwind of isolated peaks.

5.2.4 Boras

The *Glossary of Meteorology* (Huschke, 1959) defines a bora as "a fall wind whose source is so cold that when the air reaches the lowlands or coast the dynamic warming is insufficient to raise the air temperature to the normal level for the region; hence it appears as a cold wind." Cold air building up on one side of a mountain range will often be blocked. However, if it deepens sufficiently, it will eventually spill over the mountain barrier and accelerate down the opposite slope, on rare occasions reaching speeds as high as 80 kt.

The resulting low-level winds and turbulence can be a significant hazard for aircraft that are flying in the vicinity of the downrush of air caused by the bora. The danger is heightened by the fact that the exact timing and location of the air surge are difficult to forecast.

There are at least two primary causes of boras: (1) cold fronts aligned parallel to the mountain range and moving perpendicular to it, with the cold air eventually spilling over; and (2) cold outflow, from thunderstorms over or near a mountain range, that builds up to sufficient depth to spill over and down the opposite slope. The latter phenomenon is short-lived and very difficult to predict; the strong thunderstorm winds typically last less than 1 hour. However, strong downslope winds accompanying and following cold-front passages can persist for several hours. Only the initial stages of such winds have true bora or fall-wind characteristics; these winds appear to evolve into severe downslope windstorms associated with breaking waves aloft (see Section 5.1.1) and, therefore, become potentially dangerous at all altitudes, not just within a few thousand feet of the surface.

In many areas along the east slopes of the Rockies, and in particular in Colorado, prefrontal windstorms with very warm lee-side temperatures are known as chinooks; post cold-frontal windstorms with cold lee-side winds are often called bora windstorms, or boras. Thus, the term bora in these areas can mean both the initial strong burst of a cold downslope wind and any subsequent downslope windstorm. In the case of eastern-slope boras, the best indicators during the pre-flight briefing are the presence of a strong cold front moving through the area (that is, with much colder air behind the front), with associated rapid frontal movement (on the order of 30 kt or more). Surface observations (as reported in a METAR), particularly special observations of strong, rapidly changing surface winds from the west or northwest, along with decreasing temperature, may warn of bora activity. The indicators for breaking internal gravity waves, cited in Section 4.4, should not be ignored. Western-slope boras are less common and are usually associated with a strong buildup of extremely cold arctic air on the eastern slopes.

5.2.4.1 Summary Comments on Boras

- Boras are strong lee-side wind events, typically occurring after passage of a strong cold front.
- The exact time and location of a bora are difficult to forecast.
- Pilots should be alert for observations of rapidly changing winds from the west or northwest, especially when combined with falling temperatures.

5.2.5 Other Phenomena

In addition to the vortex phenomena previously discussed, vortices or strong shear zones may be generated locally by strong flow past individual mountain peaks and crags, or through gaps and passes across mountain ranges. For example, it is not unusual to see intensely swirling narrow columns of airborne snow on the downwind slopes of alpine ridges during strong wind events. Bedard (1990) shows evidence from damage patterns that are consistent with such vortices. Although it is believed that such mechanically produced phenomena are usually confined to levels near and below the highest peaks, more research is needed.

The point is that strong wind flow in the vicinity of irregular terrain can produce a multitude of disturbances of varying size and strength, many without reliable visual indicators. Their presence should be suspected when flying downwind of rugged terrain, whenever the ambient wind flow at ridge level exceeds about 20 kt.

5.2.5.1 Summary Comments on Other Phenomena

- Pilots should expect significant turbulence and the potential for loss of aircraft control when flying downwind of any isolated peak when wind speeds exceed 20 kt at ridge level.

PART II. ATLAS OF VISUAL INDICATORS

6.0 VISUAL INDICATORS OF OROGRAPHIC WIND FIELDS

Our purpose in this section is to provide an atlas of photographs that show striking examples of the strong wind flow patterns described in Part I. The goal is to assist aircrews in diagnosing the presence and qualitative strength of these features so that timely operational decisions can be made, either prior to departure or while airborne and approaching the area of strong and turbulent wind flow.

6.1 Larger-Scale Features

Lee waves that result from fairly uniform (in direction) winds over a broad area of terrain can be considered larger-scale features. Figures 6-1 through 6-4 depict wave clouds that show the local air motion through the large-scale wave events.

Figure 6-1 is a photograph of an isolated lenticular cloud near Pikes Peak, Colorado. The air is moving through the cloud from right to left in the picture. The limited vertical extent of this feature is shown by the lack of involvement of the overlying cirrus clouds. Figure 6-1b is a schematic of the lenticular with streamlines of the wind flow superimposed.

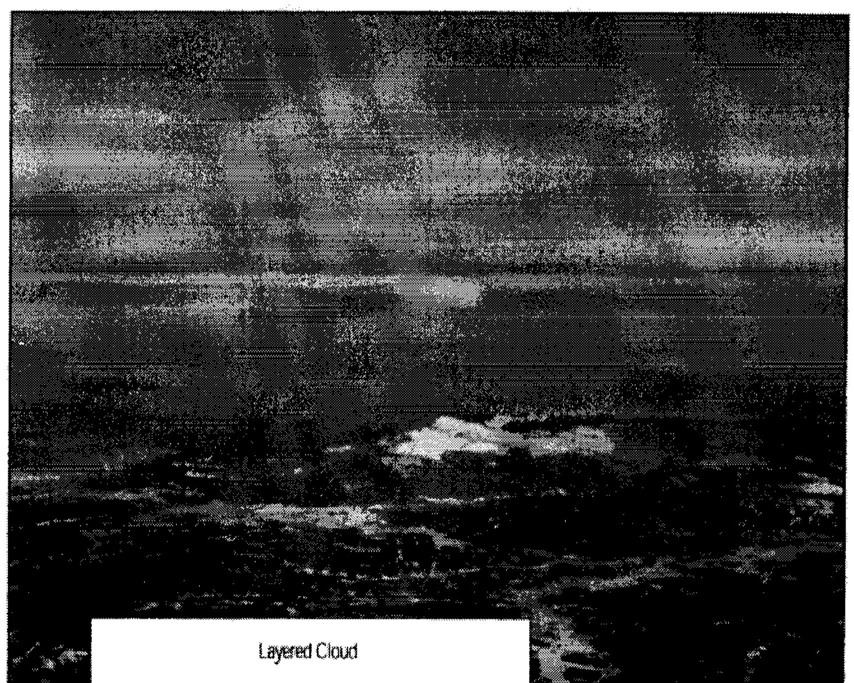


Figure 6-1a. An isolated lenticular cloud near Pikes Peak, Colorado (photograph ©, 1990, R. Holle).

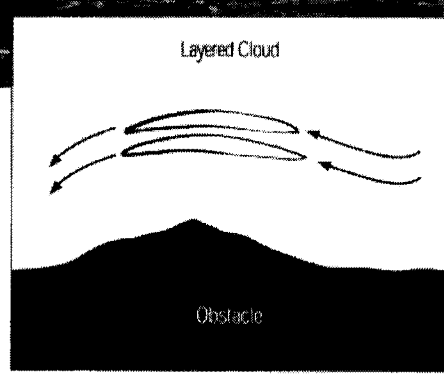


Figure 6-1b.

Figure 6-2. A wave cloud over Laramie, Wyoming (photograph ©, B. Martner).

Figure 6-2 shows another wave cloud whose layered structure makes the general pattern of the wind flow (right to left) in the wave quite evident. Note that the largest amplitudes are at lower levels in this cloud feature, implying that the most disturbed air also is at lower levels of the wave.

The wave cloud in Figure 6-3a clearly shows the air motions that have created it. The streamlines of the wind motion are added to Figure 6-3b. The wave cloud in Figure 6-4 is almost parallel to the upper level flow; this orientation may be responsible for its corkscrew appearance.

Although these photographs show outstanding examples of the way in which air motion associated with lee waves can be "mapped" by accompanying cloud features, some lee waves will not generate lenticular clouds because of a lack of water vapor in the moving air mass.

Figure 6-3a. A wave cloud over Nederland, Colorado (photograph ©, 1993, P. Neiman).

Figure 6-3b.

Figure 6-4. A wave cloud oriented parallel to the upper-level flow looking west from Dillon, Colorado (photograph ©, R. Reinking).

Figure 6-5a. Circular lenticular clouds produced by a pair of eddies in the lee of an isolated mountain peak near Nederland, Colorado (photograph ©, 1990, P. Neiman).

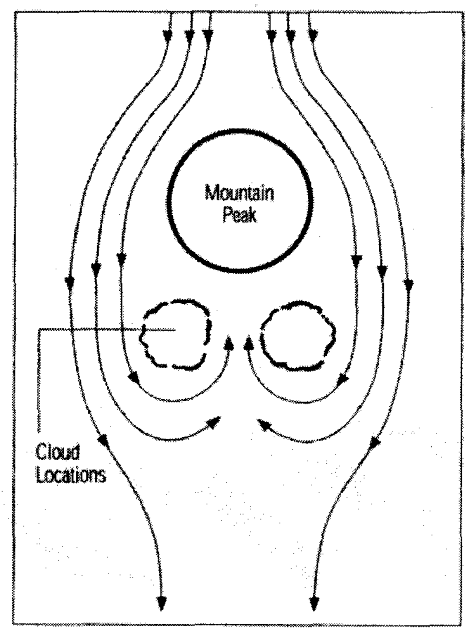


Figure 6-5b.

6.2 Smaller-Scale Flows

In the previous section, we reviewed the wave clouds and the flow patterns associated with waves that result from the large-scale movement of an air mass over a mountain range. Now we present photographs of clouds resulting from air motion over and around individual (or isolated) mountain peaks.

Figure 6-5a shows the results of flow over and around a set of higher peaks (to the left in the photograph). Various interpretations of these spectacular cloud forms are possible. One of these is shown in Figure 6-5b in which the pair of circular lenticular clouds represent a pair of eddies initiated by flow around these peaks. Another interpretation is that these lenticulars result from greater amplitude of the larger-scale mountain wave directly downwind of the peaks. Note that there are indications of disturbances in the lower portions of this cloud field, whereas the cloud appears smooth at higher levels. Significantly, the clear air below the central region of these clouds may contain intense small-scale vortices that could be hazardous for aircraft penetrating the area.

Figure 6-6 is a stunning photograph of a lenticular cloud that resulted from the strong flow around Mt. McKinley, Alaska. In this case, the wind flowing around the mountain developed a stationary eddy in the lee of the peak. Although this cloud appears quite smooth and laminar, the shear zones created by such flow perturbations have the potential to produce destructive turbulence.

Figure 6-6. A three-dimensional lenticular cloud that has developed in the strong flow around Mt. McKinley, Alaska (photograph ©, 1981, B. Martner).

Figure 6-7. A field of circular lenticular clouds that have developed in the complex flow around a number of mountain peaks in Mt. McKinley National Park, Alaska (photograph ©, 1979, B. Martner).

If such turbulence were occurring at the time of this photograph, it likely occurred in clear air away from the cloud.

An instance of flow around a number of isolated mountain peaks (also occurring at Mt. McKinley National Park) is shown in Figure 6-7. This field of circular, three-dimensional lenticulars probably has associated with it centers of strong turbulence, interspersed with areas of relative calm. Of concern to flightcrews who might attempt flight through this type of disturbed airflow is the fact that regions of strongly circulating wind flow can produce localized areas of very strong and complex air motion patterns.

Figures 6-8 and 6-9 are photographs of lenticular clouds taken from an aircraft showing the effects of flow around complicated, heterogeneous topography. Figure 6-10 concludes this section with a photograph of a lenticular cloud at sunset.

Once again, the concern with this type of smaller-scale wave activity lies in its potential for producing localized areas of severe-to-extreme turbulence in small-scale eddies. These extremely strong vortices may have no associated cloud features to make them visible as the aircraft approaches, perhaps with catastrophic results.

Figure 6-8. A view of three-dimensional lenticular clouds taken from an aircraft (photograph ©, NCAR).

Figure 6-9. A view of three-dimensional lenticular clouds north of Boulder, Colorado, taken from an aircraft (photograph ©, 1988, S. Holle).

Figure 6-10. A lenticular cloud over Boulder, Colorado, at sunset (photograph ©, B. Martner).

6.3 Rotors and Other Turbulent Zones

We have previously discussed the formation of rotor zones in association with lee waves, along with their potential for subjecting aircraft to strong turbulence and rolling moments. This section provides a sample of well-developed rotor clouds associated with lee-wave events.

Figure 6-11a depicts an example of clouds associated with vertically suppressed, trapped lee waves. These waves are occurring downstream (east, in this case) of the Continental Divide. In Figure 6-11b, the air motion is superimposed on the cloud fields. Because these clouds are flat and not very ragged, it is unlikely that turbulence within them is more than light-to-moderate.

In contrast to the vertically suppressed clouds of Figure 6-11 are the vertically enhanced clouds, viewed from the same location and also associated with trapped lee waves, shown in Figure 6-12a. The air motion in these rotors is depicted in Figure 6-12b.

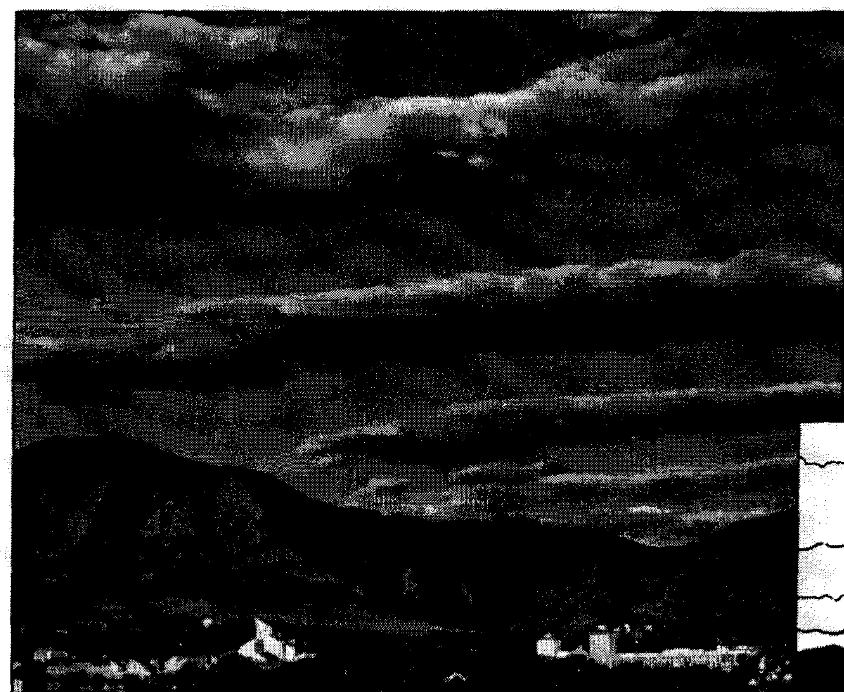


Figure 6-11a. Clouds associated with vertically suppressed, trapped lee waves at Boulder, Colorado (photograph ©, 1987, P. Neiman).

Figure 6-11b.

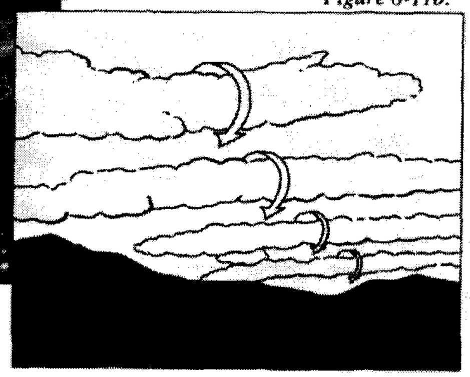


Figure 6-12a. Vertically enhanced clouds associated with a trapped lee wave at Boulder, Colorado. (photograph ©, 1992, P. Neiman).

Figure 6-12b.

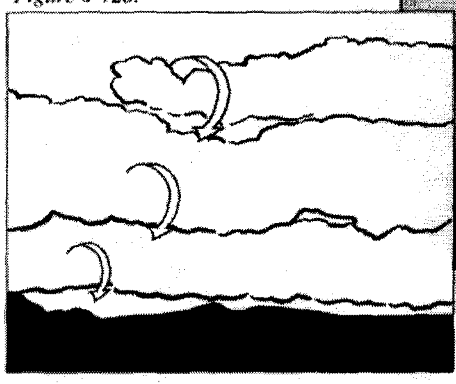


Figure 6-13a. Rotor cloud near State College, Pennsylvania (photograph ©, 1985, P. Neiman).

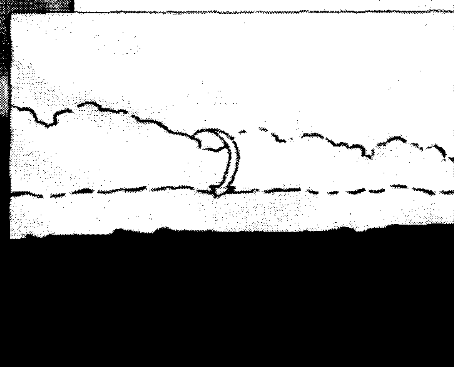


Figure 6-13b.

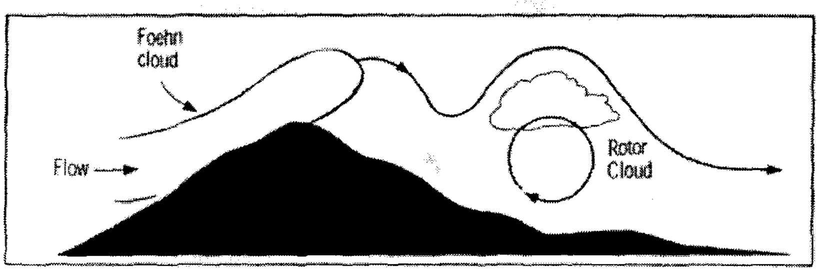


Figure 6-14. Schematic of the flow associated with a rotor zone in the lee of a mountain.

Figure 6-15a. A group of rotor clouds over Boulder, Colorado, one of which has developed a helical structure (photograph ©, 1992, F.M. Ralph).

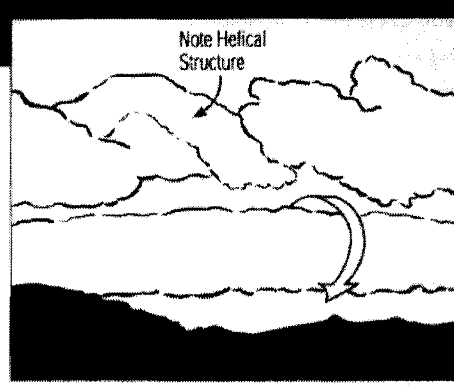


Figure 6-15b.

Figures 6-13a and 6-13b depict a rotor cloud over much lower terrain near State College, Pennsylvania. A Foehn cloud can be seen in the background of this picture. The flow associated with this feature is shown in the Figure 6-14 schematic. Note the well-defined wave that has resulted from the air motion over the ridge. The event shown in these photographs is graphic evidence that extremely high or rugged terrain is not a requirement for the development of significant wave activity. The turbulence in this situation is likely to be considerably greater than in the instance depicted in Figure 6-11a.

Rotor clouds can develop complex structures, as shown in Figure 6-15. Figure 6-15a shows a group of rotor clouds, one of which has apparently developed a helical orientation. This structure is shown in Figure 6-15b, along with the orientation of the rotary motion of the airflow within the cloud layer. The helical structure may indicate much more complex, turbulence-producing air motion in this area.

Figure 6-16 depicts a small vortex that has formed near the turbulent mixing region at the leading edge of cold, moist air at low levels, interacting with the foothills and westerly downslope flow just above.

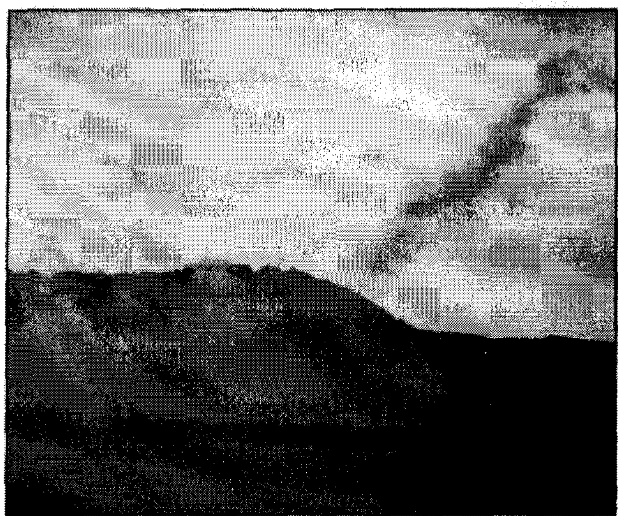


Figure 6-16. A small vortex structure formed near a turbulent mixing zone (photograph ©, A.J. Bedard, Jr.).

Figure 6-17. Turbulent cloud structures near the tropopause over Boulder, Colorado (photograph ©, 1993, P. Neiman).

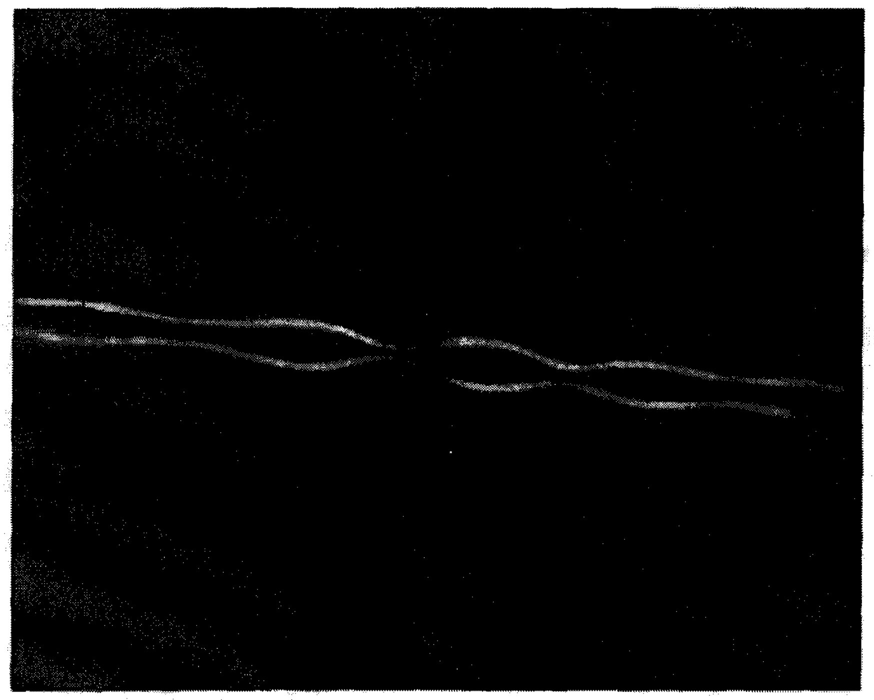


Figure 6-18. A linear contrail showing relatively smooth air (photograph ©, 1991, A.J. Bedard, Jr.)

Figure 6-17 exhibits turbulent structures in a portion of wave cloud near the tropopause. The turbulence in this cloud, together with its great altitude, is strong evidence that the cloud is produced by a breaking vertically propagating wave. The fragmented and ragged edges of the clouds in this picture are clear indicators of turbulence. Such cloud forms have been observed in coincidence with severe or greater turbulence reported by turbine aircraft at altitude.

Figure 6-19. A contrail in the vicinity of mountain wave activity near Boulder, Colorado, showing areas of turbulence (photograph ©, 1988, R. Holle).

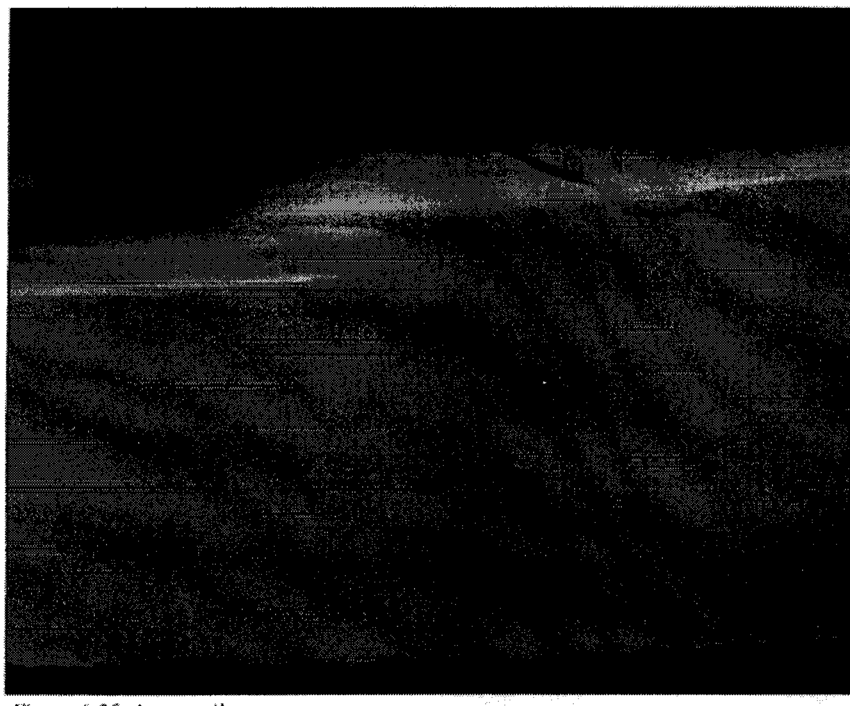


Figure 6-20. A contrail showing a significant area of turbulence aloft (photograph ©, K Langford).

6.4 Interpreting Contrails

One aid to interpreting air motion characteristics and turbulence potential at jet cruise altitudes is to study the contrails left by other aircraft. Contrails can provide a direct indication of atmospheric conditions when no clouds are present. They can yield information on atmospheric stability and wind shear and may allow the selection of a routing or cruise altitude that will remain clear of turbulence.

In relatively undisturbed air, contrails will usually remain linear and smooth in appearance (Figure 6-18). They may spread out because of the natural diffusion of the aircraft exhaust, or they may occasionally exhibit small-scale oscillations caused by the interplay of wingtip vortices in air that is only slightly disturbed. Flight through the air mass depicted in Figure 6-18 will most likely be turbulence-free.

A more typical contrail found over mountainous terrain is shown in Figure 6-19. Although only a few lenticular clouds suggest the presence of a mountain wave, the contrail reveals a detailed history of the rather turbulent passage of this aircraft through the wave area.

The aircraft was flying from left to right in the picture and, because the contrail does not exhibit violent mixing or dissipation over most of the area shown, strong and persistent turbulence was probably not encountered. However, it appears that the aircraft had encounters with large-scale (on the order of 10 km) waves, with superimposed strong chop at several locations.

Another significant event is located at the point in Figure 6-19 where the contrail has nearly vanished because of the turbulent mixing that is occurring. The amplitude of the wave is largest here, while the wavelength is shorter than is found in the other portions of the visible contrail. This is an indication of a major vertically propagating gravity wave. Supporting evidence of this is the lenticular cloud that appears above the exiting contrail on the right side of the picture. This latter area should be avoided, or if that is not possible, the aircraft should be configured for turbulent air penetration prior to the turbulence encounter. The contrail appears to straighten out as it moves east of the mountain range, implying that wave energy was being transported vertically, rather than downstream at the same altitude.

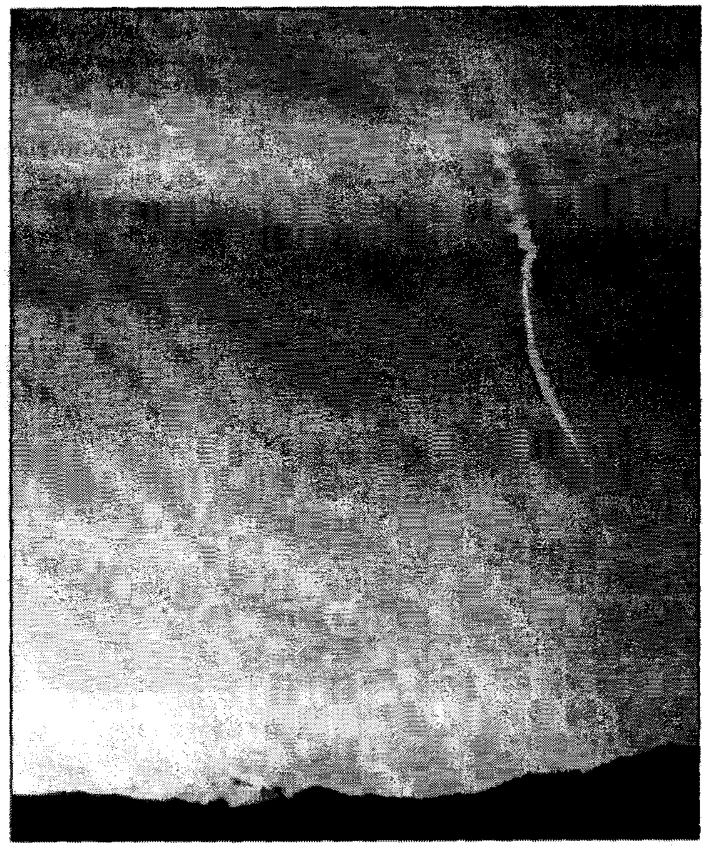


Figure 6-21. Contrail with turbulent zone, over Boulder, Colorado (photograph ©, F.M. Ralph).

Other turbulent histories are evident from the contrails in Figures 6-20 through 6-23. In Figure 6-20, the aircraft flew beneath an area of standing lenticular clouds, encountering a significant area of turbulence that peaked at the upstream edge of the cloud. Here the atmosphere has strong rising motion and the contrail is highly contorted and twisted, in contrast to that seen in the rest of the photograph. Once the aircraft cleared the leading edge of the cloud area, the contrail became smooth and laminar, indicating that the turbulence had probably ceased.

Figure 6-22. Contrail associated with lenticular and rotor clouds, showing very turbulent conditions aloft (photograph ©, K. Langford).

Figure 6-21 shows yet another encounter with a turbulent zone near the upwind edge of a lenticular cloud. The highly turbulent mixing of the contrail at this point leaves no question about the strong shear present, a characteristic of this upstream region. Figures 6-20 and 6-21 point to the fact that the upwind edge of an area of lenticular clouds is frequently quite turbulent. As the aircraft in Figure 6-21 continued on course, it encountered a longer-wavelength oscillation and then a smooth flight path. It should be noted that similar concern should be given to the downwind edge of lenticular clouds.

Figure 6-23. Contrail located above rotor and lenticular clouds, indicating smooth conditions aloft (photograph ©, 1988, R. Holle).

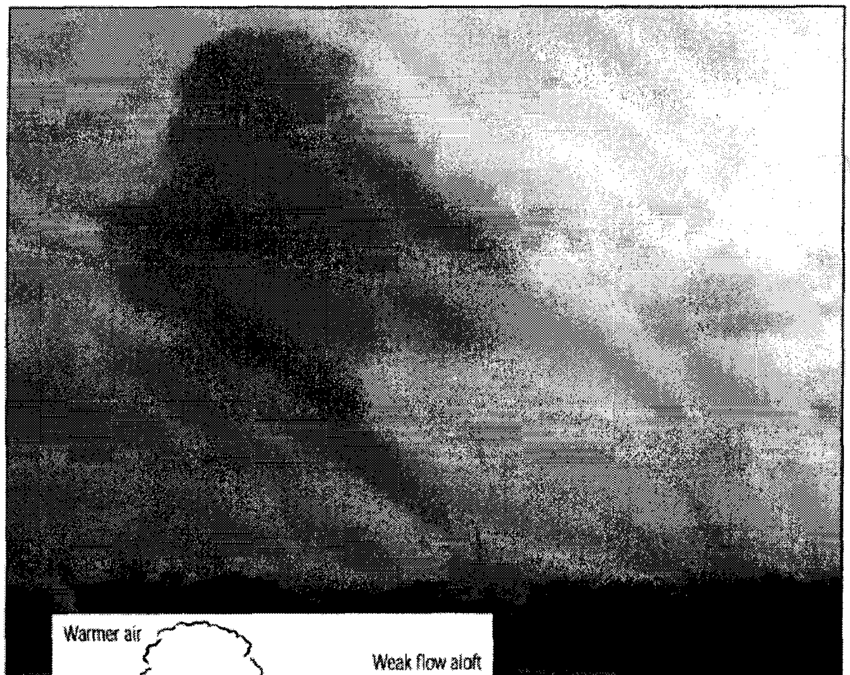


Figure 6-24a. Smokestack plumes with an inversion layer in Boulder, Colorado (photograph ©,1992, P. Neiman).

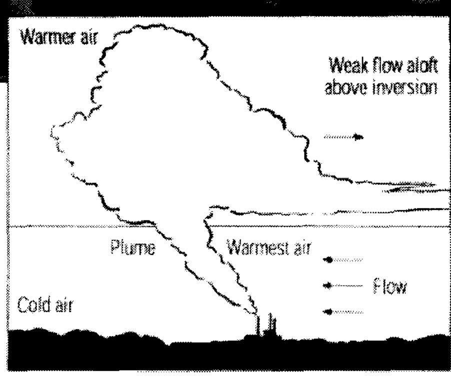


Figure 6-24b.

A striking photograph of very turbulent conditions is shown in Figure 6-22. This contrail, located below lenticular clouds and above an area of rotor clouds, shows evidence of wave disturbances and very turbulent conditions that were likely manifested as severe turbulence. In this instance, disturbed parcels are violently displaced on very small horizontal scales. The longer-wavelength disturbance in Figure 6-22 is likely contributing to passenger and crew discomfort, but the more serious problem is defined by the puffy nature of the contrail.

The final contrail photograph (Figure 6-23) shows that (as most pilots know) there are always exceptions to the rules applied to descriptions of the atmosphere. Even though lenticular clouds and rotor clouds indicate the potential for turbulence, a contrail often can provide some indication of the most turbulence-free altitude in such an area. In Figure 6-23, the cloud signature is indicating a rotor cloud topped by a series of lenticular clouds that are related to vertical gravity wave propagation. However, the contrail history indicates that the conditions encountered by the aircraft were relatively benign. Thus, the presence of laminar contrails in areas that contain mountain waves can aid pilots in selecting turbulence-free altitudes.

6.5 *Other Visual Indications of Air Motion Near Complex Terrain*

The atmosphere presents a number of opportunities for an observer with a trained and discriminating eye to diagnose the processes that are occurring in the nearby motion field. We have already reviewed a number of these atmospheric signposts. In this final section of our atlas of visual indicators, we present a potpourri of photographs that expand upon the issue of interpreting the type and level of activity of air motion near mountainous terrain.

Figure 6-24a depicts the plumes from several smokestacks located in Boulder, Colorado. Perhaps you have encountered similar patterns on your way to the airport before a trip. In this example, the light wind at lower levels is blowing from right to left, and the plumes do not significantly expand with height. This indicates that the steam is moving upward rapidly and that the plume is much warmer than the low-level air. As the plumes penetrate higher, the largest plume breaks through the stable (inversion) layer into warmer air and expands more rapidly. This process is shown schematically in Figure 6-24b. Although not depicted in Figure 6-24, had the wind flow above the inversion been stronger, the plume would have been sharply bent downwind as it penetrated the stable layer and encountered the wind shear.

Figure 6-25. Blowing snow near mountain peaks, indicating likely wave activity (photograph ©, R. Reinking).

Figure 6-26. Low-level wind indicators on a lake surface (photograph ©, 1988, A.J. Bedard, Jr.).

Figure 6-27. Wave cloud occurring above a layer of weak instability (photograph ©, NCAR).

Blowing snow around mountain peaks, shown in Figure 6-25, is an indication of strong wind and turbulence, and the likelihood of mountain wave activity. Similarly, wave disturbances on the surfaces of lakes can warn of strong and turbulent air motion near the ground (Figure 6-26). The latter wave features can be seen as flecks of ground clutter on airborne radar imagery of larger bodies of water.

Although we have discussed the fact that mountain waves require a degree of stability for their existence, they may occur with weak convection nearby. This situation is shown in Figure 6-27, with a wave cloud overlying a field of shallow convective clouds. Figure 6-28 shows a similar situation near Mount Shasta, California, in which the convection below the cap cloud has probably resulted from heating of the lower terrain upstream of the mountain.

Figure 6-28. Cap cloud over Mt. Shasta, California, with low-lying weak convection (photograph ©, 1972, R. Reinking).

Figure 6-29. Banner and cap clouds occurring in the Grand Tetons, Wyoming (photograph ©, B. Martner).

Condensation occurring in air that has been constrained to ascend a mountain or ridge can produce banner clouds and cap clouds. Figure 6-29 depicts two closely spaced peaks in the Grand Tetons of Wyoming, the left peak exhibiting a banner (or flagging) cloud and the right peak showing a cap cloud. These features are signs of strong flows and turbulence near ridge levels. Blowing snow would provide similar clues of this air motion.

Figure 6-30a. Cap cloud, or cloud associated with a bora (photograph ©, K. Langford).

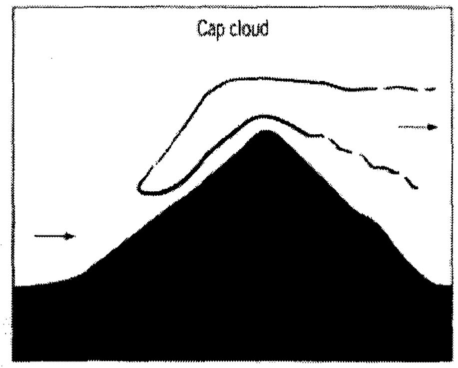


Figure 6-30b.

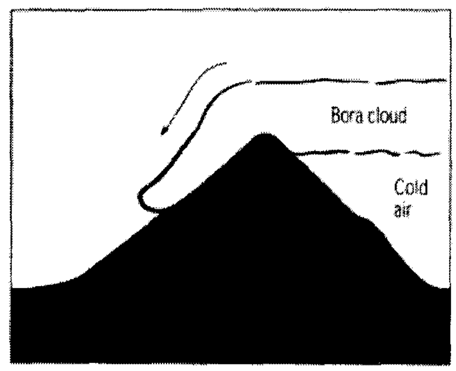


Figure 6-30c.

Figure 6-31. A Foehn wall near Boulder, Colorado (photograph ©, 1988, R Holle).

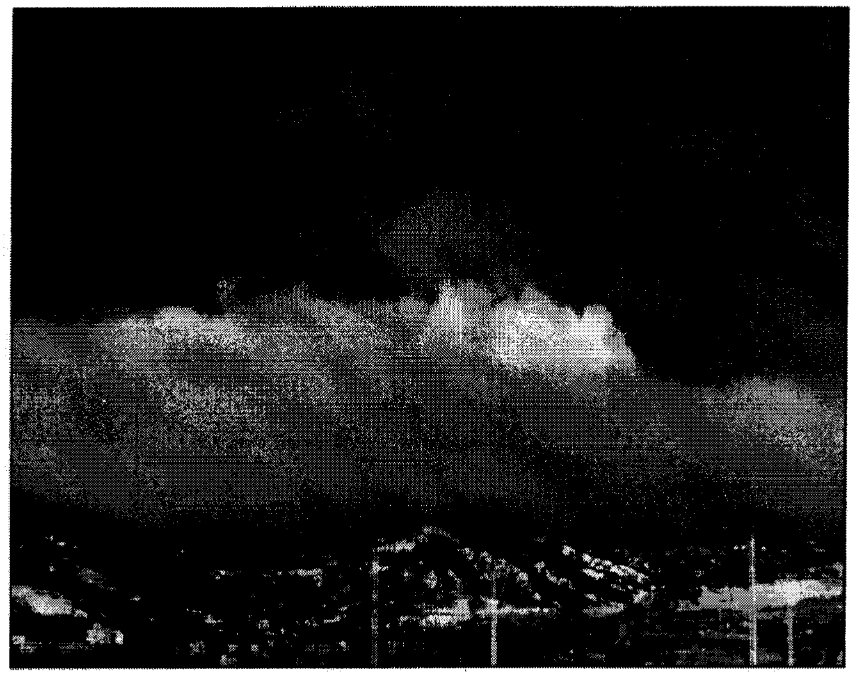


Figure 6-30a shows a meteorological situation that can have two physical explanations. The first is that this feature may be a cap cloud that occurs as flow from left to right forces air upward on the upwind side of the mountain. As the moist air moves vertically, condensation occurs and forms a cloud that follows the form of the mountain peak. Cap clouds are usually restricted to the immediate area of the peak.

An alternative explanation for the feature shown in Figure 6-30a is that cold, moist air building up on one side of a mountain range has surged over the top, descending rapidly on the other side because of its greater density compared to the air lying in the valley below. The leading edge of the system could produce a cloud form similar to that shown in this photograph. This is an example of a bora, which we have previously discussed. This alternative mechanism is shown schematically in the companion Figure 6-30c and can be distinguished from the original position by the extent of the associated cloud field (the cloud field associated with a bora has a much greater extent).

A cloud feature similar to the cap cloud is the Foehn wall, also produced by condensation of water vapor in rising air as it crosses a mountain peak. Figure 6-31 shows a well-developed Foehn wall near Boulder, Colorado. Yet another example of a Foehn cloud is seen in Figure 6-32. In this case, the rising motion has formed a cap cloud that merges with a higher cloud layer that is the result of a mountain wave over the ridge.

Figure 6-33 shows banner clouds streaming off several peaks and ridges. The blowing snow in the foreground is indicative of strong winds. There also is some blowing snow in the canyon and up its left side. All of these features are indicators of strong winds near ridge level. The flattened appearance of the banner clouds suggests that flow across the mountains is somewhat stable. This, combined with the strong winds, points to the likelihood of significant wave activity.

Figure 6-32. Cap clouds over Owens Valley, California (photograph ©, 1974, R. Reinking).

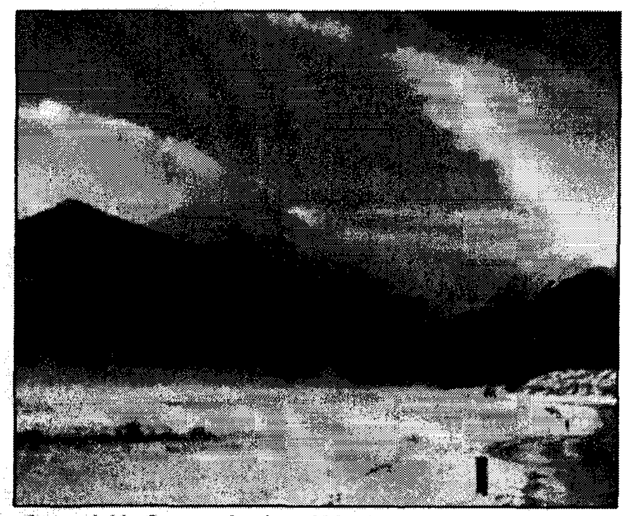


Figure 6-33. Banner clouds and blowing snow (photograph ©, 1967, R. Reinking).

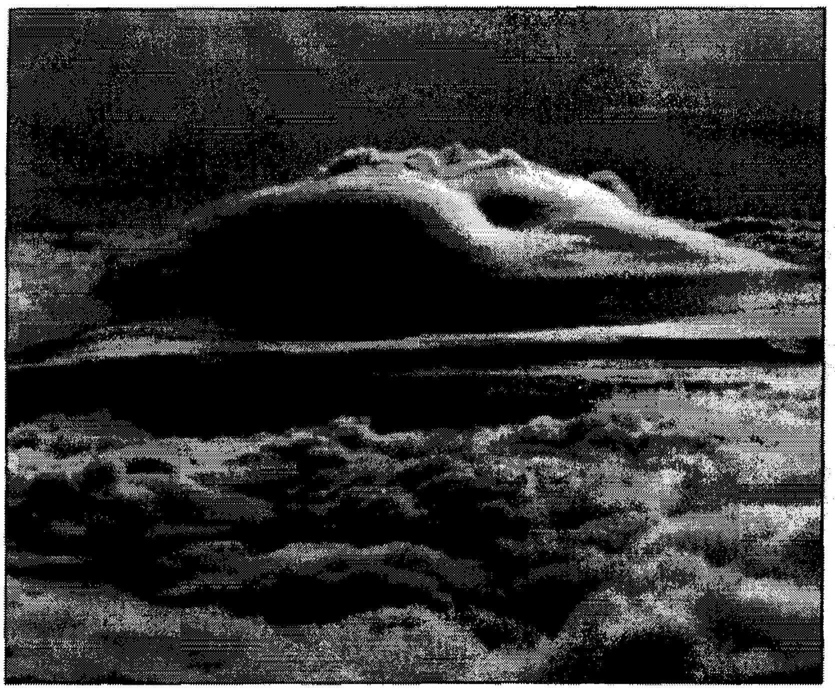


Figure 6-34. Cap cloud over Mt. Rainier, Washington (photograph ©, K. Langford).

We close this section with a striking picture of a cap cloud that has developed over Mt. Rainier, Washington (Figure 6-34). The air near ridge level has formed a capping inversion that is suppressing the development of the convective plumes at lower levels.

PART III. SUMMARY

7.0 REVIEW OF MAJOR CONCEPTS

Based on our current level of knowledge, several conclusions can be drawn regarding the effects of severe mountain-induced wind events on aviation operations:

A. The likelihood of encountering a severe mountain-induced wind event increases with:

   1) The height of the mountain or ridge above the level of the surrounding terrain;

   2) Wind direction that is nearly perpendicular to the terrain axis;

   3) Ambient wind speed at mountain-top level of 20 kt or greater (becoming more hazardous as wind speed increases);

   4) Wind speed that changes slowly with altitude;

   5) A stable atmosphere.

B. As is the case with thunderstorms, the strength of a given wave or associated eddy/rotor zone can vary from being relatively weak to containing updraft/downdraft components and wind shear layers strong enough to overcome the control authority of an aircraft or lead to catastrophic airframe failure.

C. Although cloud features may be present and can give qualitative indications of the presence/severity of mountain waves, in many cases the atmosphere is too dry for cloud formation and no visual warning is available. However, pilots should stay alert to warnings of potentially turbulent air revealed by contrails from other aircraft.

D. The most turbulent eddies may be too small to be resolved by current operational observing systems; as a result, pilots must anticipate the likelihood of wave development and the existence of shear zones and turbulence, based on the presence of the features given in paragraph A above.

E. Until the results of anticipated research are in, including recommended pilot response to a severe turbulence encounter or aircraft upset (which is likely to be aircraft-specific), the best practical advice is to avoid takeoff and landing in areas where mountain waves and rotor zones are present or forecast.

This is true especially when high terrain is located within 20 nm upwind of the airport.

F. For high-altitude turbulence, consideration should be given to changing the route of flight to avoid areas where moderate or severe turbulence is forecast. If turbulence is anticipated, the aircraft should be operated at the manufacturer's recommended turbulent air penetration speed prior to entering the turbulence.

G. When operating in visual meteorological conditions, a number of indicators may warn of potentially hazardous winds. These include:

   1) Whitecaps on the surface of lakes, implying surface winds in excess of 25 to 30 kt;

   2) Ragged appearance of clouds, particularly the upwind and bottom edges of lenticular clouds;

   3) Blowing dust or snow near the surface, particularly with evidence of rotary motion;

   4) Obviously turbulent motion of air blowing through trees;

   5) Smokestack plumes (turbulent mixing of the smoke at some level within the lower atmosphere, or a calm layer near smokestack level capped by strong "bending" and turbulence in the smoke plume at the overlying inversion level).

H. Watch for remarks in METARs, such as PRJMP or PRESRR. Ask the FSS briefer for Center Weather Advisories and Meteorological Impact Statements relevant to the planned flight.

As stated at the beginning of this AC, there is much that we do not know about the likelihood of occurrence and the possible impact of many of the potentially hazardous mountain winds described herein. Similarly, we cannot directly detect the presence of many of the smaller disturbances, nor can we accurately forecast their time and place of onset. It is hoped that future research will result in improved detection and forecast techniques, thereby improving safety for all aircrews operating in mountainous areas of the country.

We conclude this AC with one more photograph, which eloquently illustrates the idea that we still have much to learn about the complex atmospheric flows in the vicinity of high terrain. Figure 7-1 is a picture of clouds resulting from a complicated wind pattern that has produced a pair of three-dimensional lenticulars in the lee of Long's Peak, Colorado. The lowest level of cloud is most likely a rotor. What is not so certain, however, is the source of the circular gap in the cloud field, located in the center of the photograph. It could be the result of a rotor or of some other process yet unknown.

Again, the message is clear: Although we know quite a bit about the generalized motions of air masses that are constrained to move over rough terrain, we understand much less about the processes leading to mountain-induced severe wind events. This is particularly true for the smallest and most intense eddies that can develop near the terrain, translate downstream, and eventually dissipate. Pilots should approach areas of likely disturbances with extreme caution and with well-planned paths of escape and retreat. This is most important when the aircraft is configured in a high-drag, low-energy state, such as during takeoff and landing. As is the standard in all aircraft operations, when flying near rough terrain, make safety and conservatism your flying companions.

Figure 7-1. Clouds associated with a complicated flow regime in the lee of Long's Peak, Colorado (photograph ©, A.J. Bedard, Jr.).

GLOSSARY OF KEY TERMS

Advection—the horizontal transport of atmospheric properties, by wind motion.

Amplitude—the maximum displacement of a wave.

Banner cloud—a cloud plume often observed to extend downwind from mountain peaks, even on otherwise cloud-free days.

Bora—a fall wind whose source is so cold that when the air reaches the lowlands or coast the dynamic warming is insufficient to raise the air temperature to the normal level for the region; hence, it appears as a cold wind.

Cap cloud—a stationary cloud on or hovering above a mountain peak.

Chinook—see Foehn.

Conditionally unstable—the state of a column of air when its temperature lapse rate is less than the dry adiabatic lapse rate but greater than the moist adiabatic lapse rate. When an air parcel is displaced vertically, it will be stable if unsaturated and unstable if saturated.

Doppler lidar—Doppler lidar equipment (similar to radar) uses a laser that is reflected by atmospheric particles of dust and smoke.

Dry adiabats—lines on an adiabatic chart that show the dry adiabatic rate for rising or descending air. They represent lines of constant potential temperature.

Eddy—a small volume of air (or any fluid) that behaves differently from the larger flow in which it exists.

Fall wind—a strong, cold wind that blows downslope off snow-covered plateaus.

Foehn—a warm, dry downslope wind on the lee side of a mountain range. Also called chinook.

Gravity wave—a wave disturbance in which gravity and buoyancy interact to produce the wave motions.

Gravity-shear wave—see Kelvin-Helmholtz (K-H) wave.

Horizontal shear—see Wind shear.

Inversion—a layer of the atmosphere in which temperature increases with altitude.

Karman vortex street—two parallel rows of alternately shed vortices along the wake of an obstacle.

Kelvin-Helmholtz (K-H) wave—a wave occurring in an atmosphere with a stable lapse rate of temperature. K-H waves derive their energy from strong vertical wind shear.

Lenticular cloud—a lens-shaped or airfoil-shaped cloud usually (but not always) associated with a mountain wave.

Orographic—related to mountains.

Parcel of air—an imaginary, small body of air a few meters wide that is used to explain the behavior of air.

Period—the time interval between passages, at a fixed point, of a given phase of a wave.

Phase speed—the speed of movement of a wave.

Rawinsonde—a balloon-borne instrument that transmits wind data and other observed parameters to a ground-based receiving station.

Rotor cloud—a turbulent cloud formation found in the lee of mountains, in which the air rotates around an axis parallel to the mountains.

Shear—see Wind shear.

Stable atmosphere—an atmosphere in which the temperature lapse rate is less than the moist adiabatic lapse rate, and which is resistant to vertical motions.

Trapped lee wave—an atmospheric disturbance in the lee of a mountain or ridge, constrained from propagating vertically by strong overlying wind shear.

Tropopause—the boundary between the troposphere and the stratosphere.

Unstable atmosphere—a state of the atmosphere in which the lapse rate of temperature is great enough that a vertically displaced parcel will be warmer than its surroundings and will rise because of buoyancy without need for an external lifting force.

Unstable wave—a wave whose amplitude grows with time.

Vertical shear—see Wind shear.

Vertically propagating wave—an atmospheric disturbance in the lee of a mountain or ridge that develops and transports its energy vertically.

Vortex—an atmospheric disturbance that possesses rotational motion.

Wavelength—the distance between two adjacent maxima or minima of a periodic disturbance.

Wind shear—a change in direction and/or speed of the wind.

- Horizontal wind shear—for the purposes of this AC, the change in direction and/or speed of the wind at constant altitude.
- Vertical wind shear—for the purposes of this AC, the change in direction and/or speed of the wind with height.

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