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.

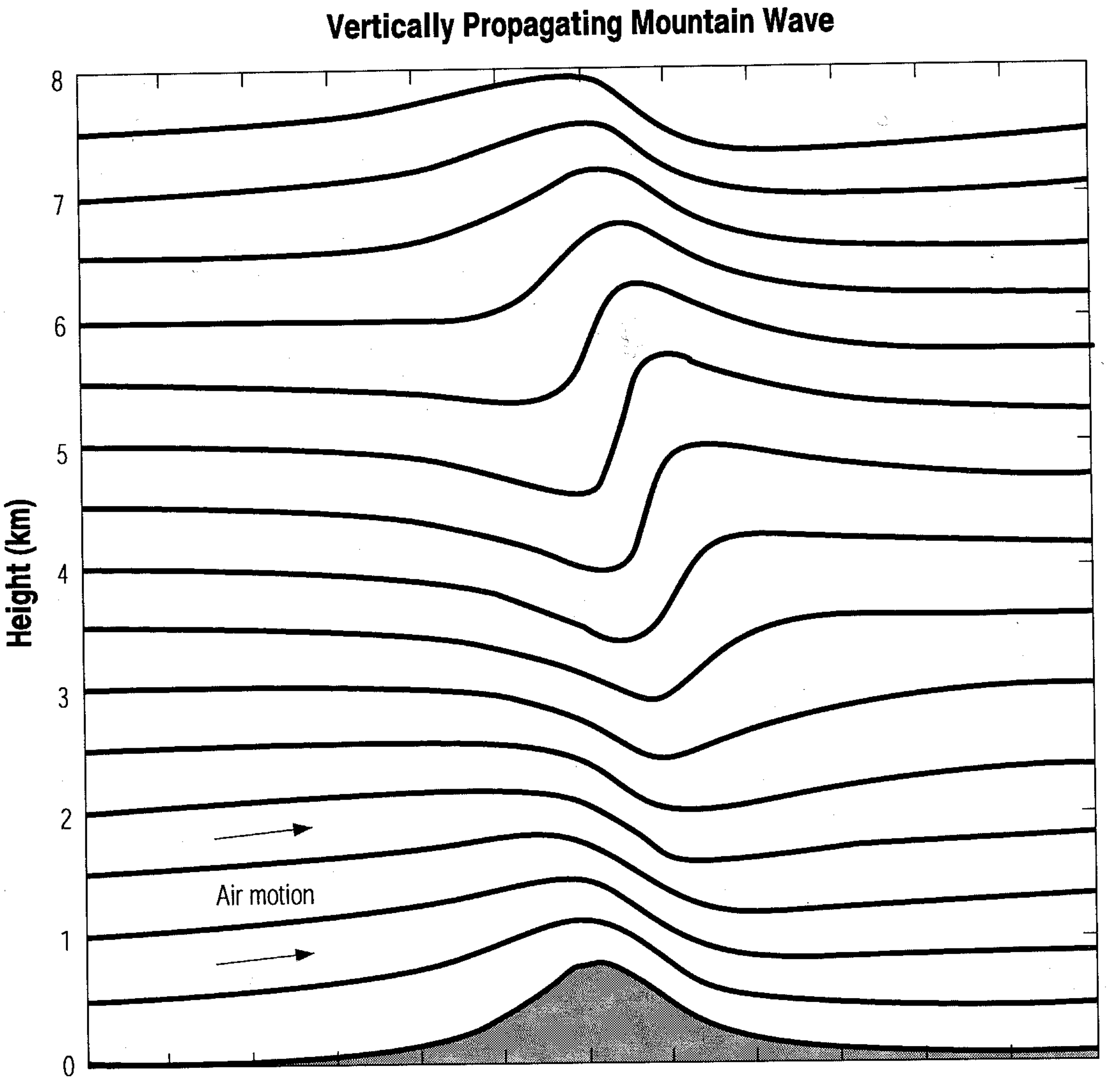


Figure 5-1. Schematic of a vertically propagating mountain wave (after Durran and Klemp, 1983).

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.

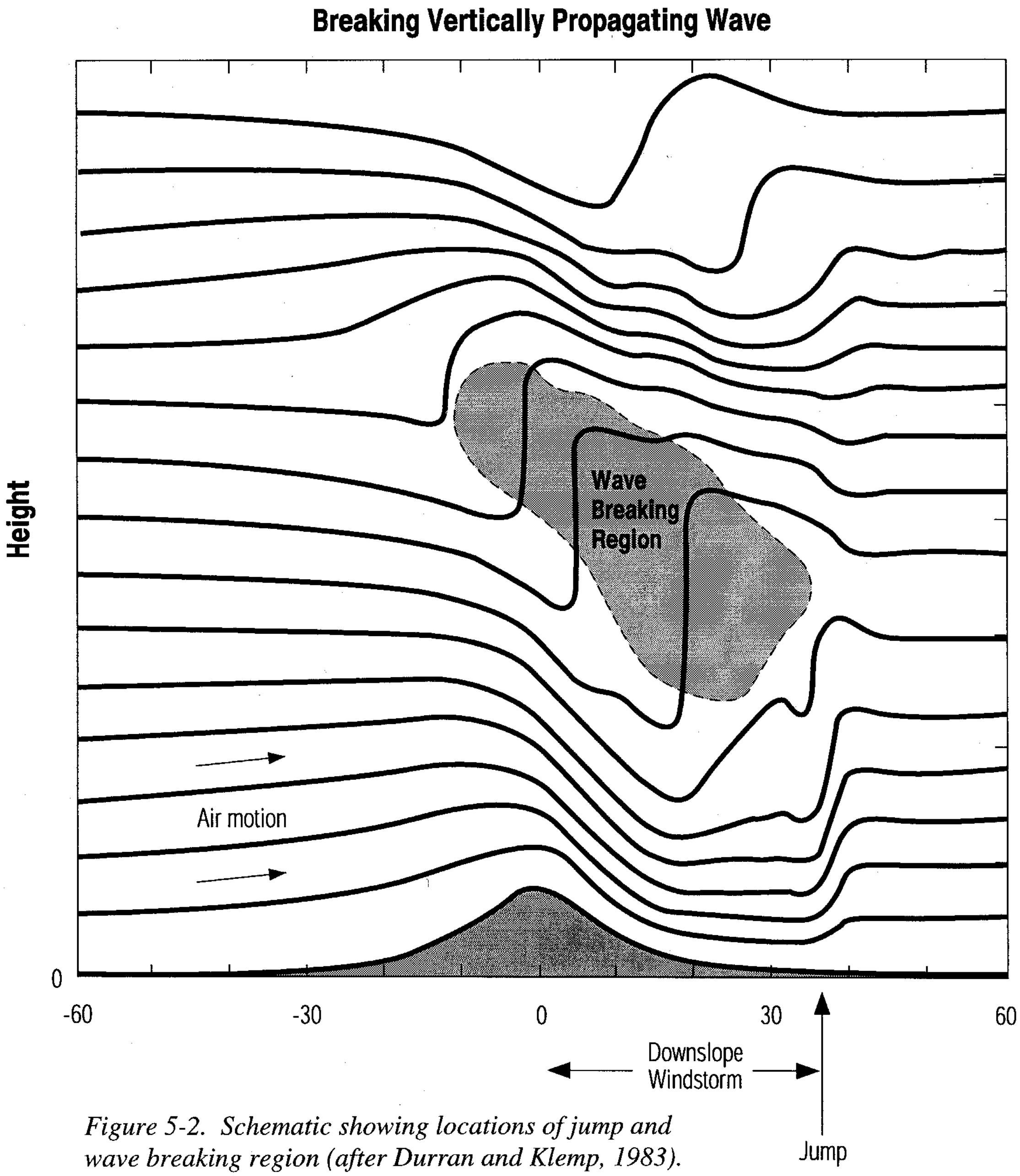


Figure 5-2. Schematic showing locations of jump and wave breaking region (after Durran and Klemp, 1983).

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.

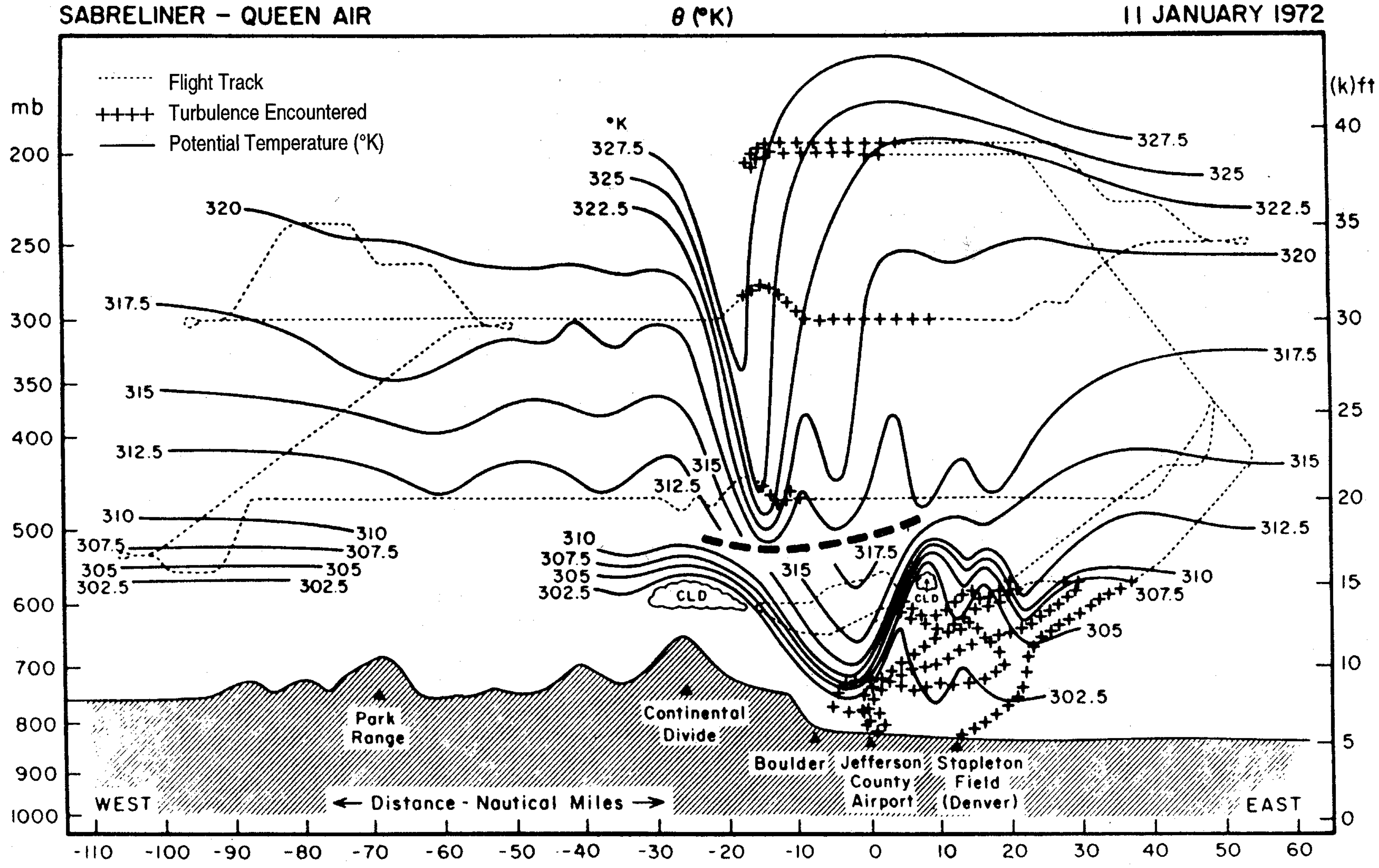


Figure 5-3. Aircraft flight tracks and turbulence encounters associated with a wave-induced high-wind event (taken from Lilly, 1978).

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.

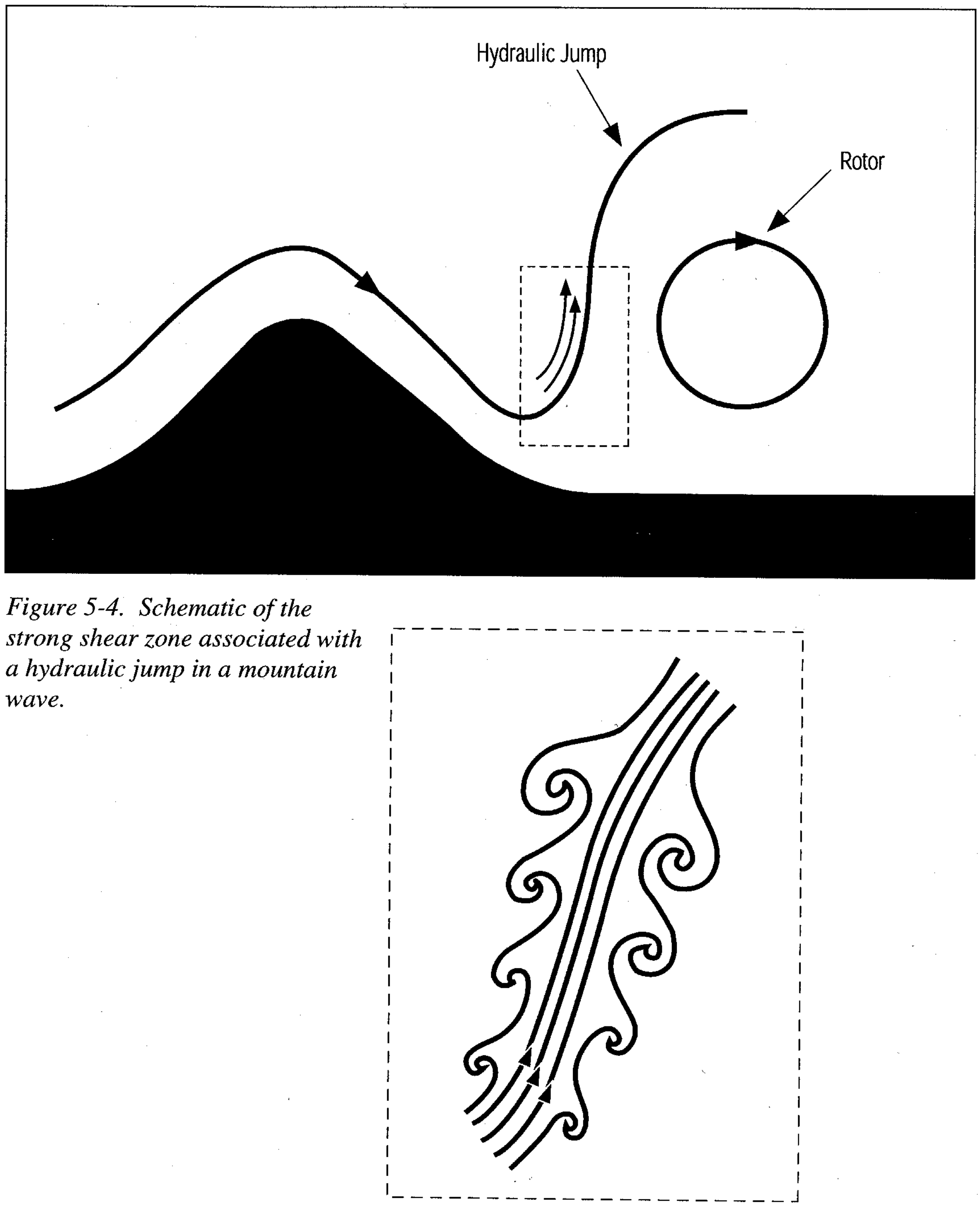


Figure 5-4. Schematic of the strong shear zone associated with a hydraulic jump in a mountain wave.

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.

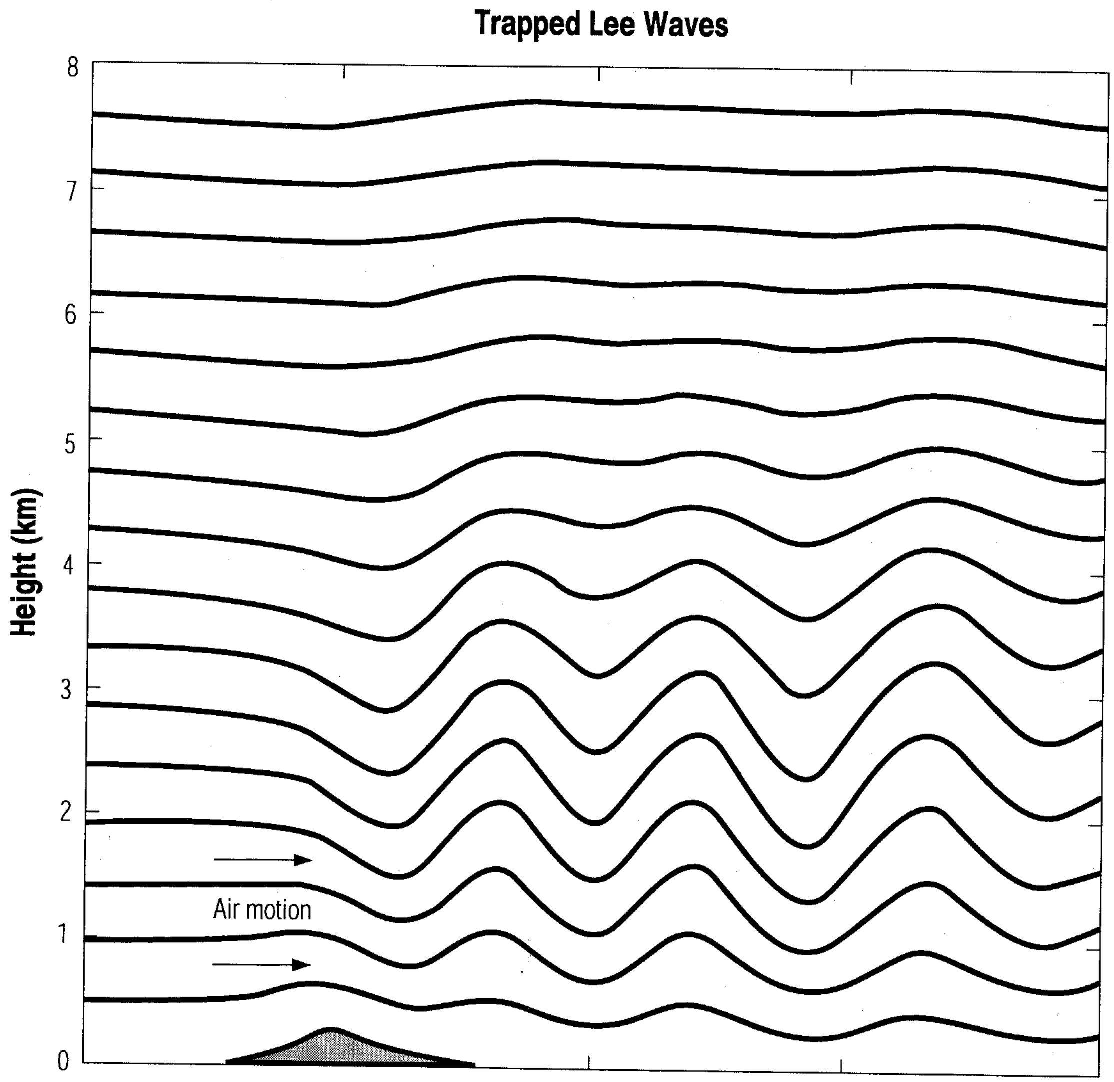


Figure 5-6. Computer simulation of trapped lee waves behind a 300-meter-high mountain.

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.

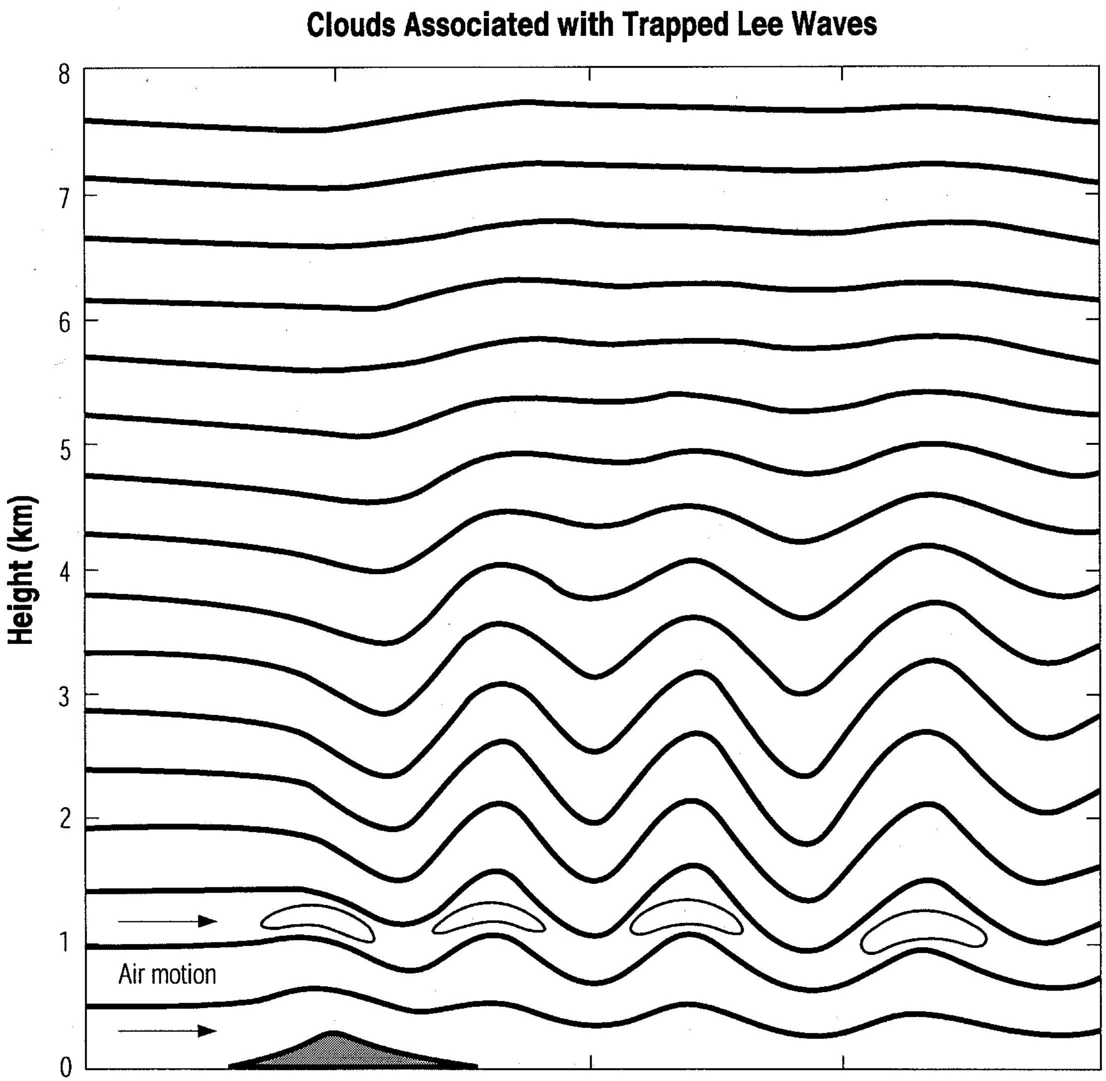


Figure 5-7. Lenticular clouds associated with a trapped lee wave (after Durran and Klemp).

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

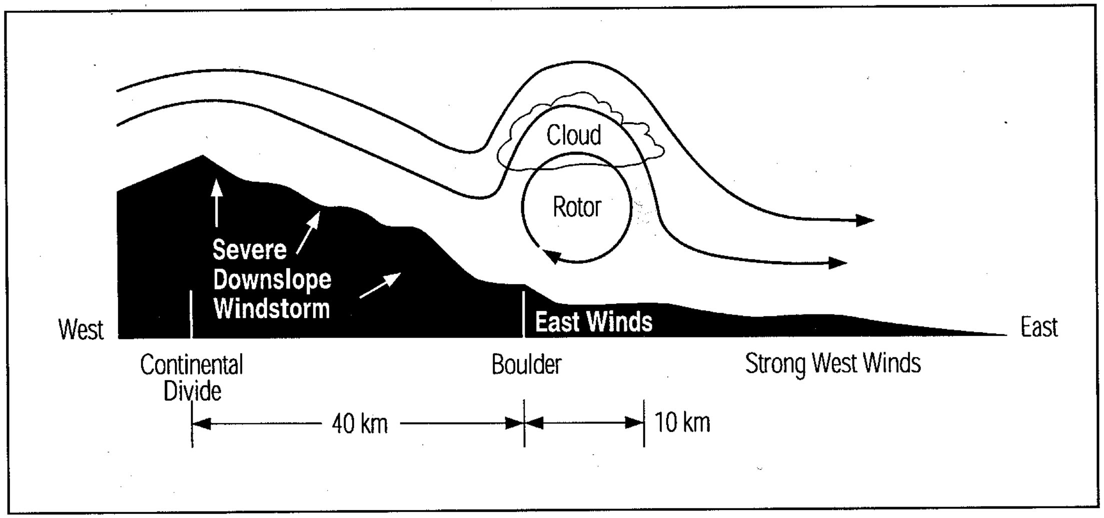
Determination of the likelihood of trapped lee waves should be made using the same forecast and observed data as for vertically propagating waves. Both are favored by stability in the lowest several thousand feet above the level of the mountain top. If this condition is met, then the simplest procedure 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.

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

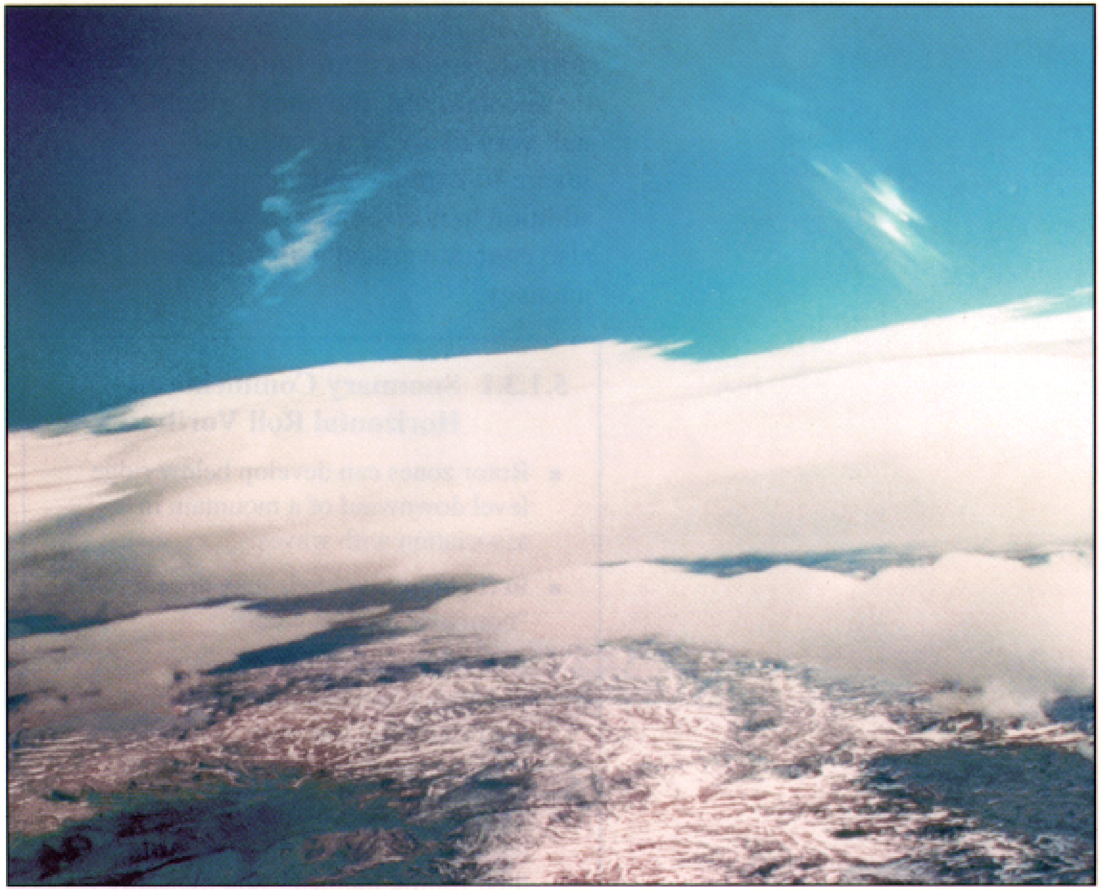


Figure 5-10. View from aloft of a wave cloud and associated rotor (photograph ©, NCAR).

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.