Figure 5-13b.

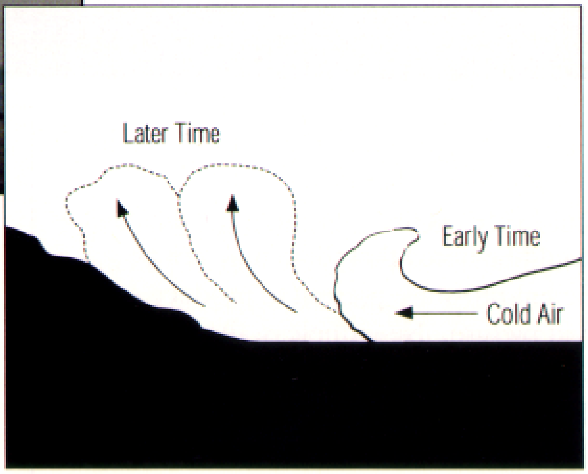


Figure 5-13c.

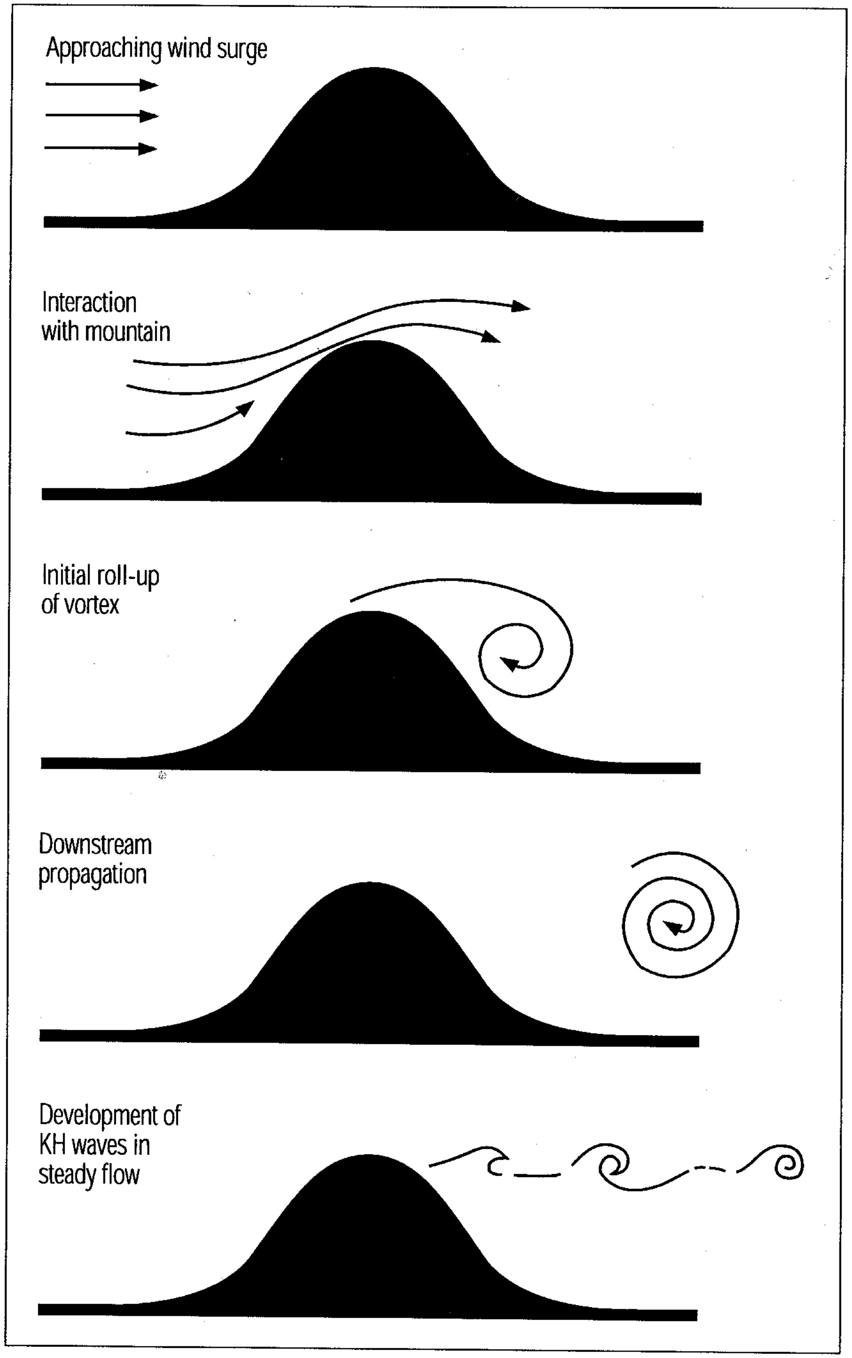
5.2.2 Non-Steady Horizontal Roll Vortices (Moving Horizontal Vortices)

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.

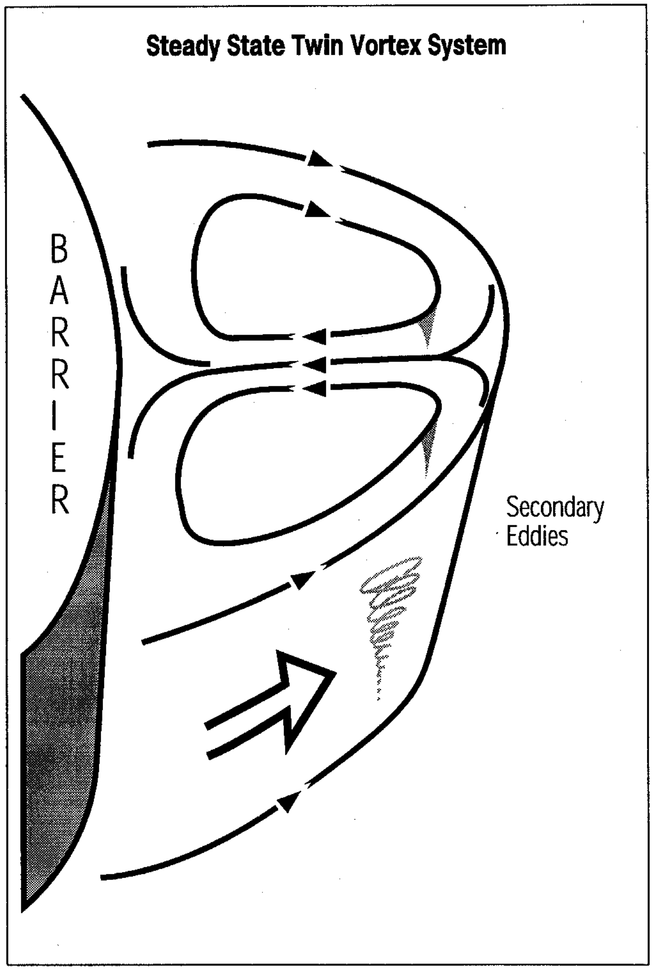


Figure 5-16. Schematic of vertically oriented vortices generated in the lee of an isolated mountain peak.

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).

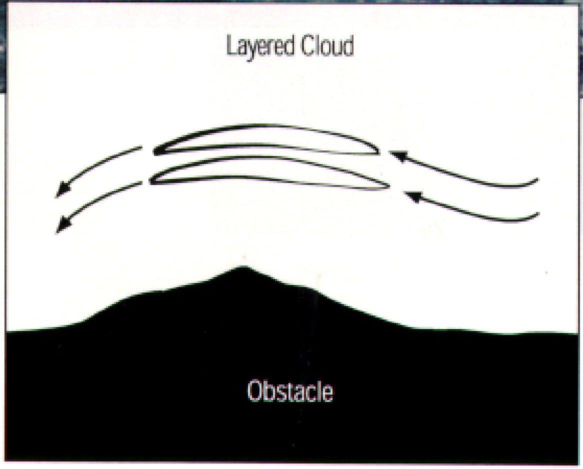


Figure 6-1b.

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.