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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