

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).*

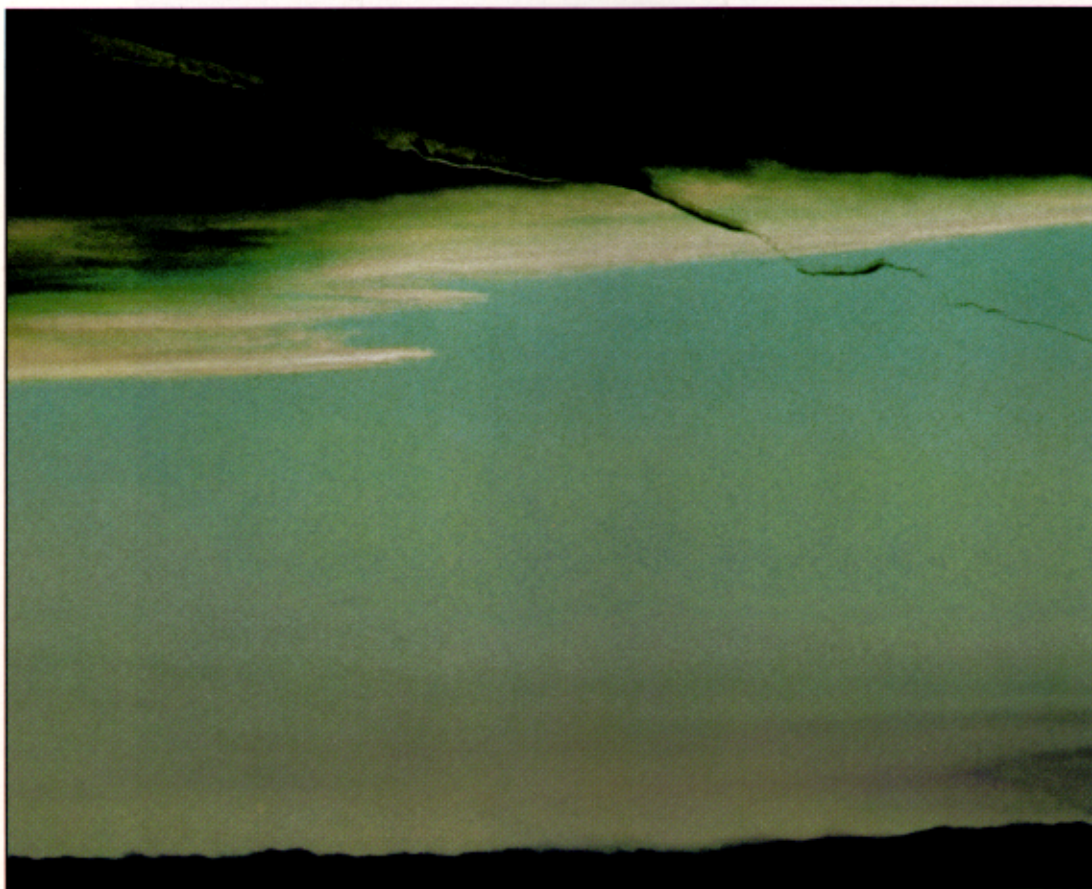


Figure 6-20. A contrail showing a significant area of turbulence aloft (photograph ©, K Langford).

#### 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.

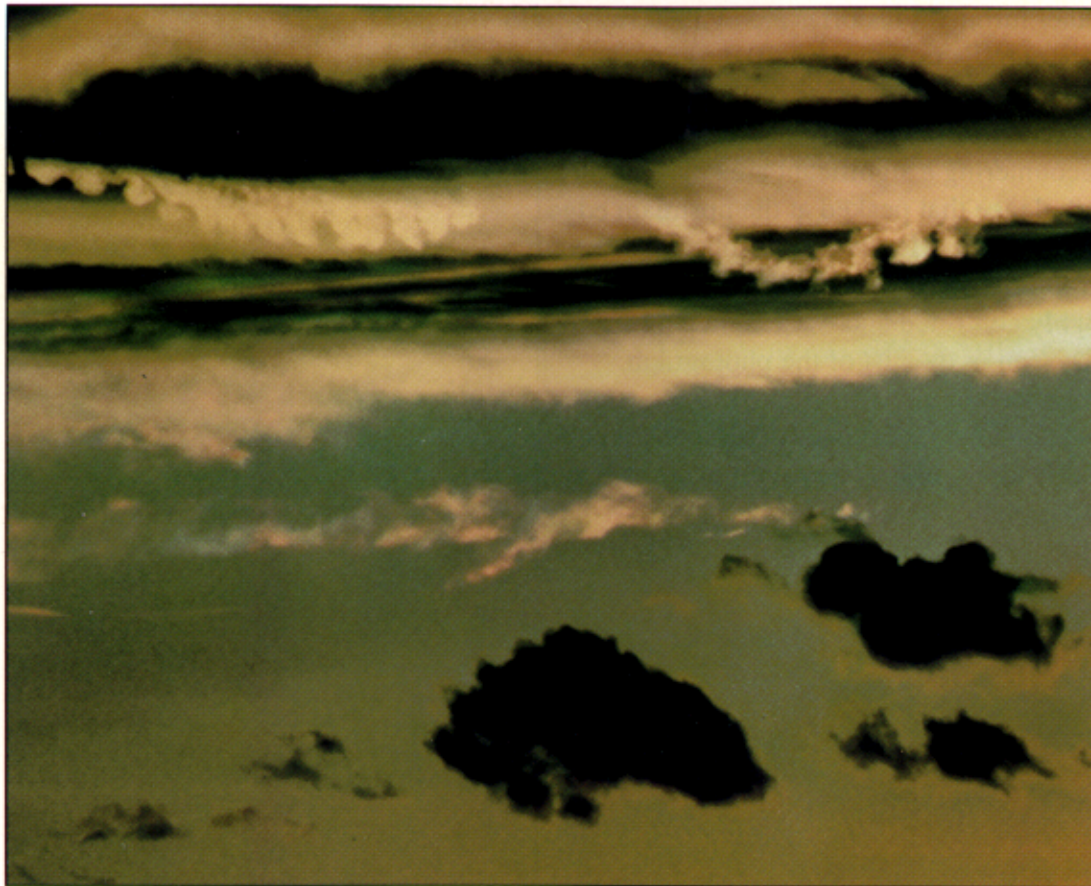
Figure 6-21. Contrail with turbulent zone, over Boulder, Colorado (photograph ©, F.M. Ralph).



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the order of 10 km) waves, with superimposed strong shear several locations.

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).*



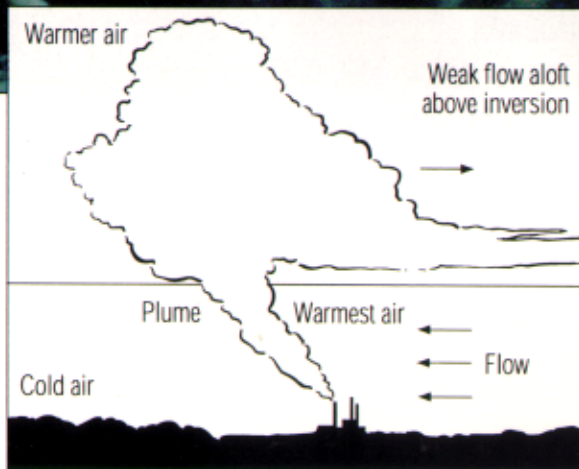


Figure 6-24a. Smokestack plumes with an inversion layer in Boulder, Colorado (photograph ©, 1992, P. Neiman).

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.

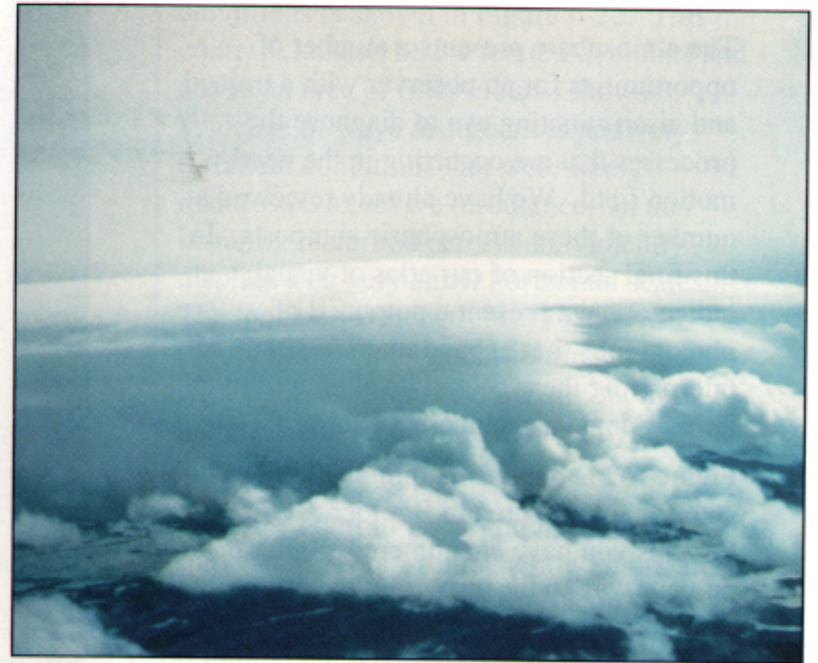
Figure 6-24a depicts the plumes from several smokestacks located in Boulder, Colorado. Perhaps you have encountered similar patterns on your way to the airport before a trip. In this example, the light wind at lower levels is blowing from right to left, and the plumes do not significantly expand with 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).

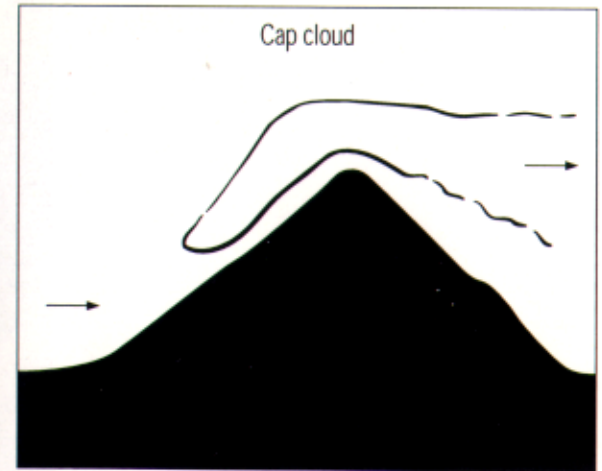


Figure 6-30b.

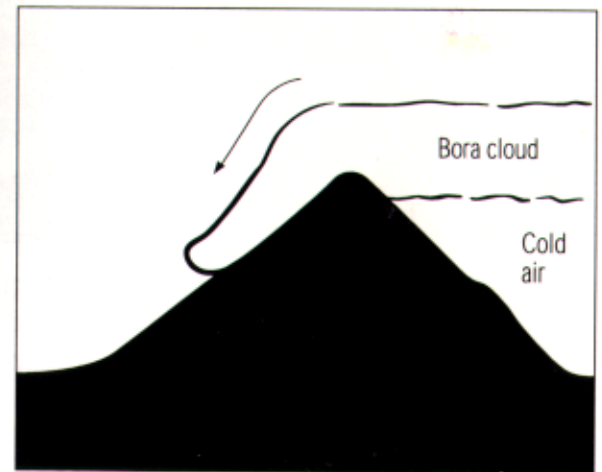


Figure 6-30c.