AC 00-57

Hazardous Mountain Winds

And Their Visual Indicators

FEDERAL AVIATION ADMINISTRATION

AC 00-57

Hazardous Mountain Winds
And Their Visual Indicators

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

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Cover photo: over Boulder, Colorado,
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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.

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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

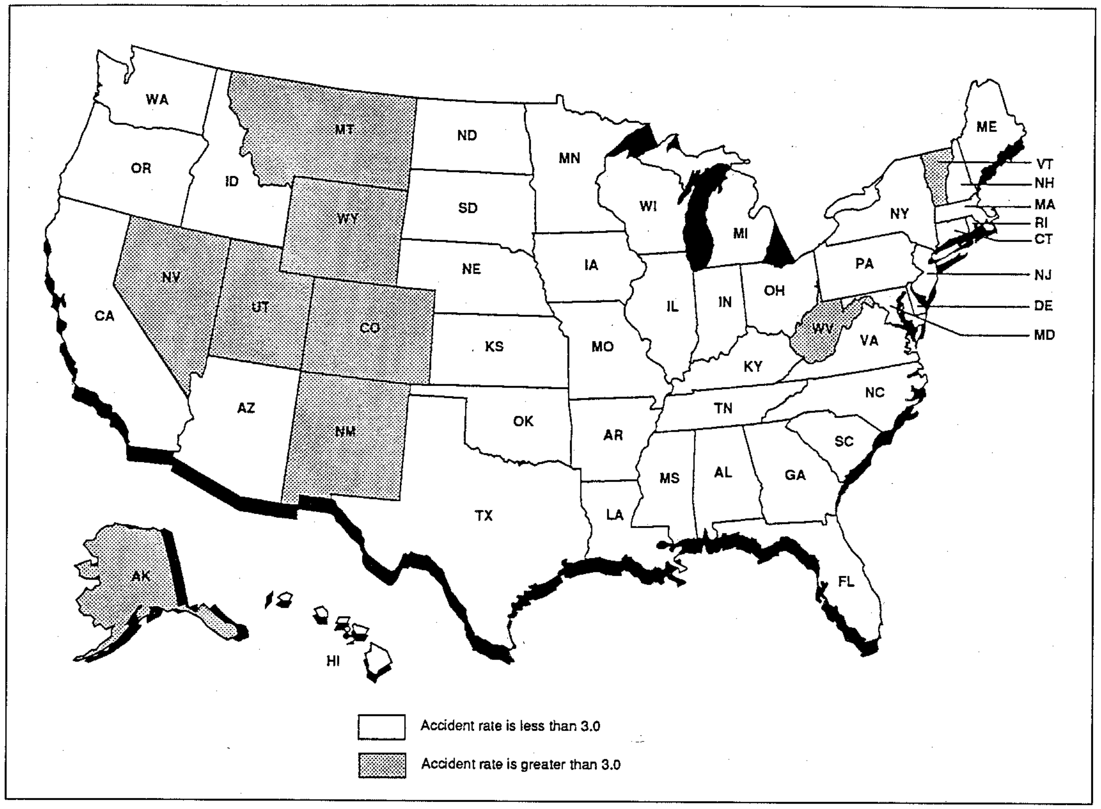


Figure 1-1. States with general aviation accident rates over 3.0 per 100,000 operations, Fiscal Year 1992.

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.

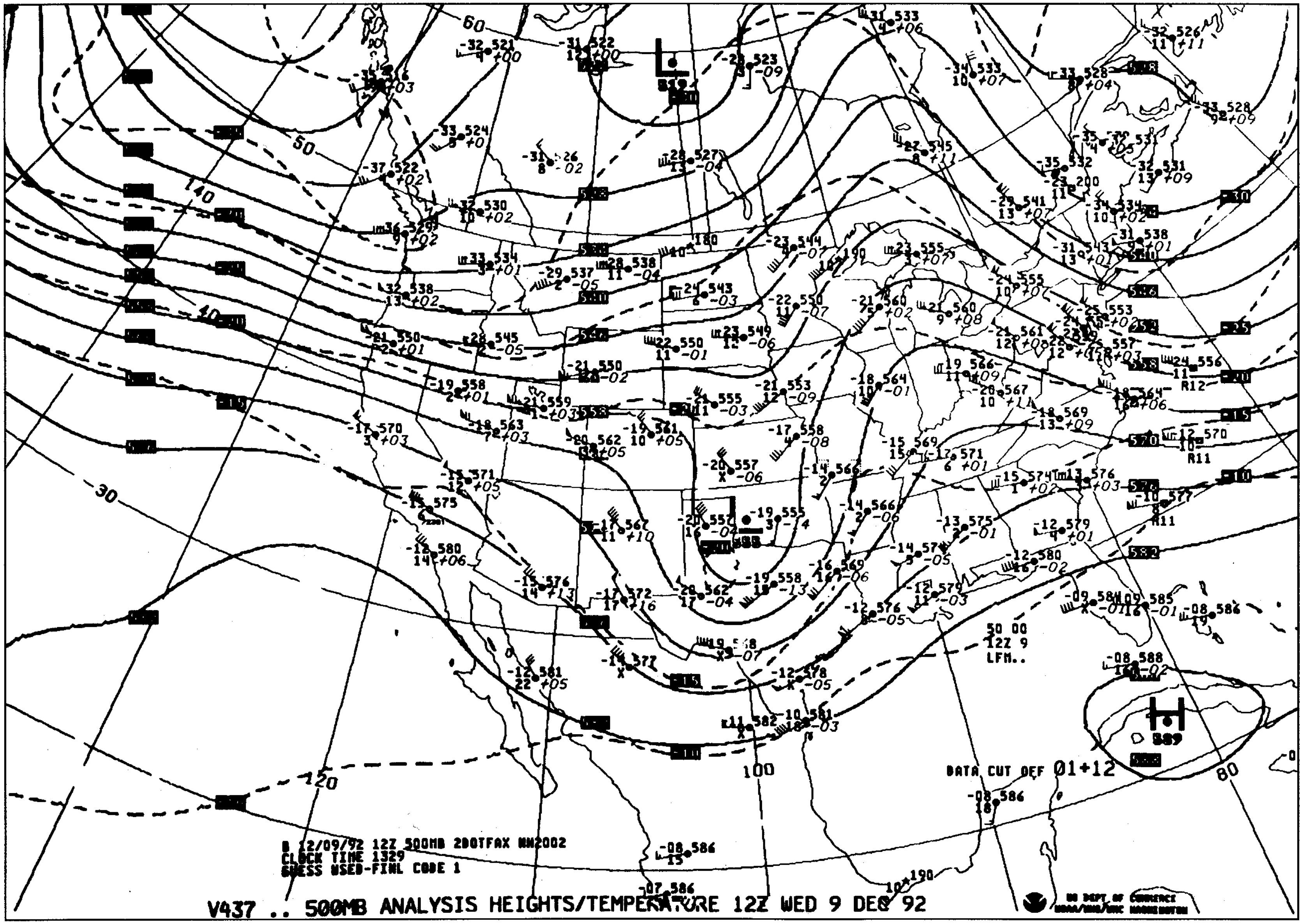


Figure 4-1. Example of a large-scale atmospheric wave pattern as seen on a National Weather Service constant pressure chart (500 mb). The solid lines are approximately parallel to the wind flow at this level. Rawinsonde observations are plotted. This example happens to be a few hours before a DC-8 experienced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

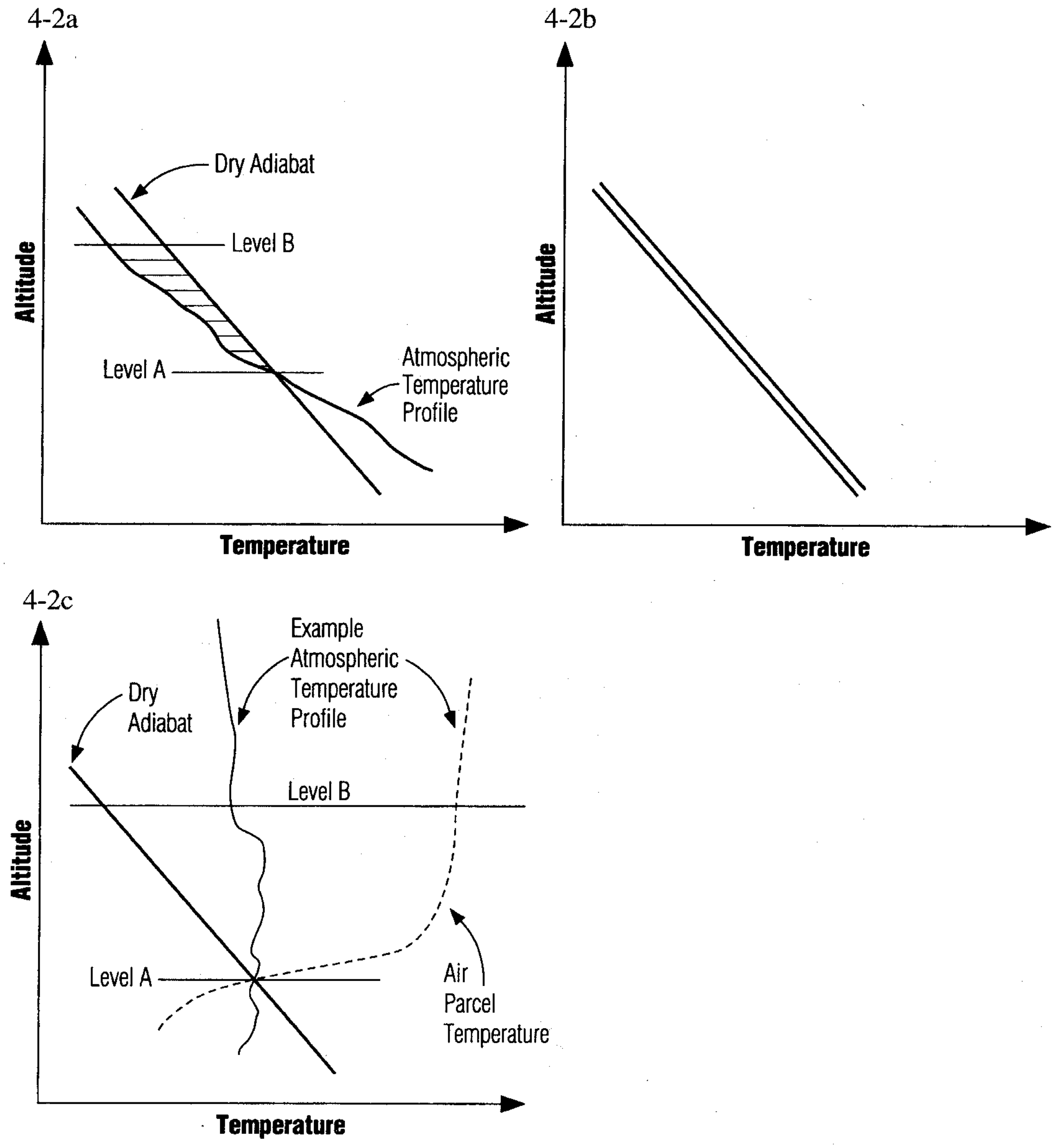
Mountain ranges can generate very strong, large amplitude gravity waves that can produce serious hazards to mountain flying. For that reason, we will consider their properties in some detail. In nonmountainous areas, shear-induced waves are a primary source of turbulence at altitude. In the vicinity 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.

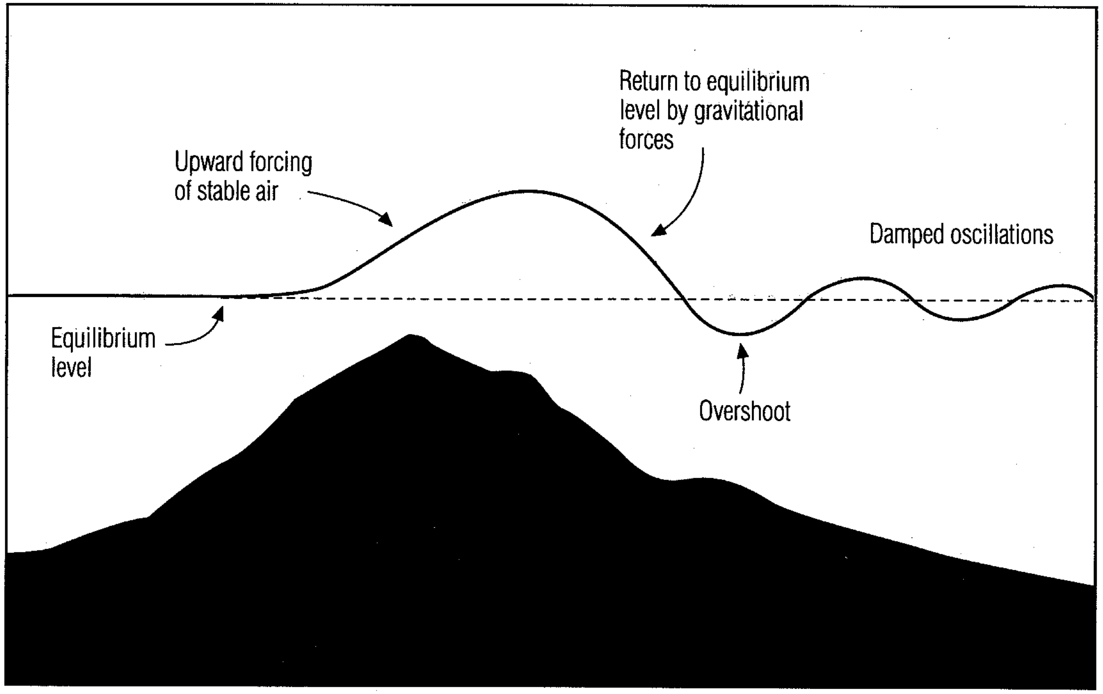


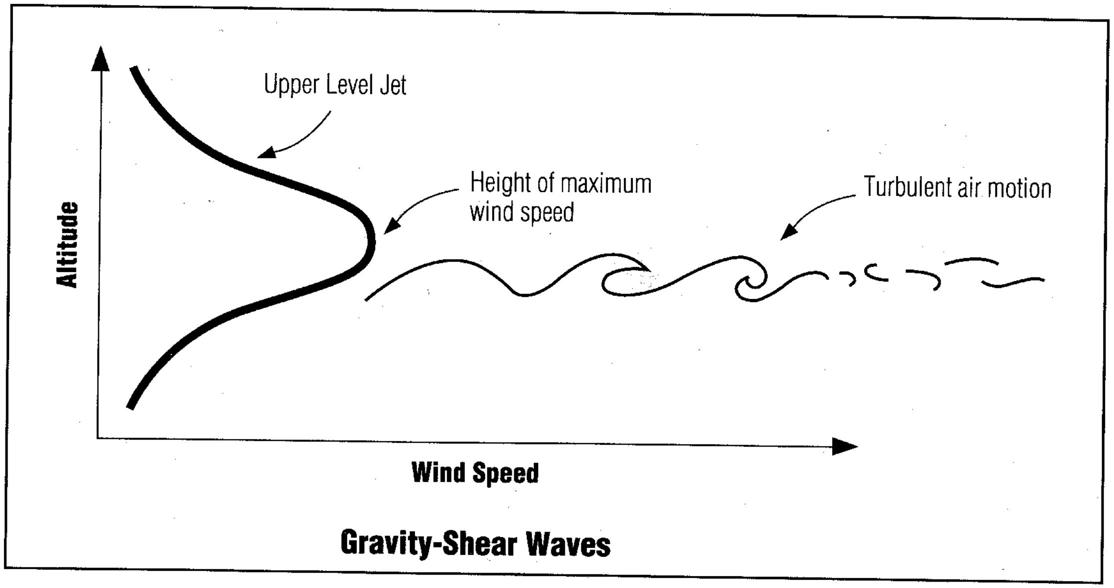
Figure 4-3. Oscillations associated with a gravity wave.

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.

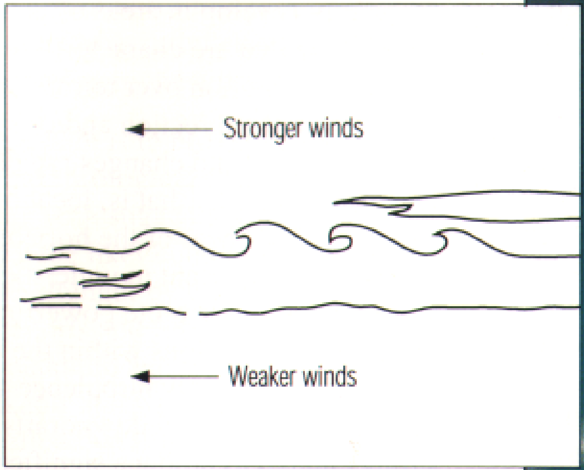


Figure 4-5b.

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).