

## THE MOUNTAIN WAVE

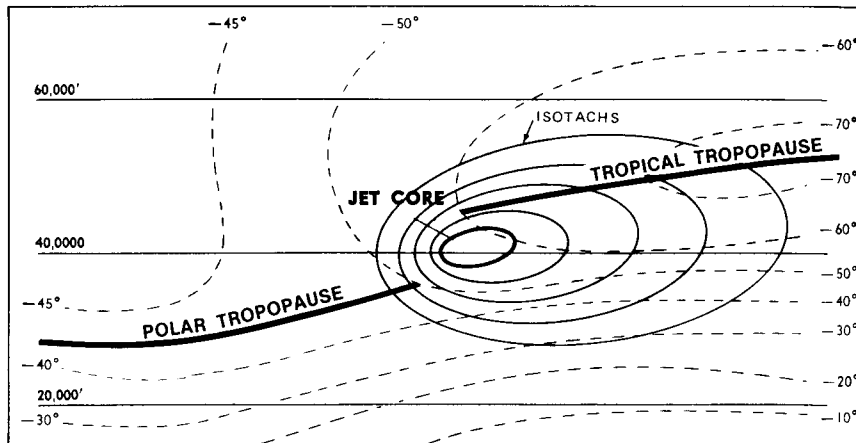
### INTRODUCTION

When wind blows over mountains a phenomenon may occur that is known as the *mountain wave*, *standing wave*, *lee wave*, *standing lenticular*, *ACSL* (*alto cumulus standing lenticular*), or just *plain wave*.

The wave is much like water in a stream, where it may pass over an obstruction such as a log, and then flow down, making a trough, then up, down, up, and down many times, making a diminishing succession of crests and troughs.

Meteorologists forecast mountain waves with a high degree of accuracy. But, the average general aviation pilot may not have a knowledge of mountain waves, the conditions favorable for their formation, or the ability to identify the wave. The wave tends to be deceitful. The reason is that it is associated with 60–80 miles of visibility, leading to the misconception that the air is smooth. When planning a mountain flight with a mountain wave present, you should know what to expect and plan your flight accordingly.

During the summer the intermountain west experiences possibly two mountain waves per week, with more during the spring and fall, increasing to five or six a week during the winter months. The reason for this increase is the more stable air of winter along with the fact the jet stream shifts farther south in the winter than in summer and becomes considerably stronger. Also, during the night, mountain waves become stronger when the air becomes more stable.



A cross section of the upper troposphere and lower stratosphere showing the tropopause and associated features. Note the "break" between the high tropical and the lower polar tropopause. Maximum winds occur in the vicinity of this break.

COURTESY "AVIATION WEATHER"

### JET STREAM

From our past knowledge of the weather, we recall the layer of air extending upward from the earth's surface is the troposphere. An abrupt change in the temperature lapse rate marks the boundary between the *troposphere* and the *stratosphere*. The line of demarcation between the two is called the *tropopause*. The height of the tropopause varies from about 65,000 feet over the Equator, where the air is heated and rises, to 20,000 feet or lower over the poles. The tropopause varies with the seasons, lowering with the approach of winter and its diminishing temperature. The tropopause is not continuous, but generally descends step-wise from the Equator to the poles. These steps occur as "breaks."

The jet stream is a narrow, shallow band of strong winds, meandering through the atmosphere at a level which typically occurs in the "break" between the polar tropopause and tropical tropopause. There may be more than one jet stream. Since the jet stream is located near the tropopause, it is usually a matter of concern for the "jet drivers." There are times, however, during the winter when a "polar outbreak" causes the jet stream to dip down to 15,000 feet or as low as 10,000 feet. This occurs more frequently than you would suspect.

### POLAR FRONT

The earth's orbit around the sun forms an ellipse. Since the poles are inclined  $23\frac{1}{2}^\circ$  from the perpendicular to the plane of the earth's orbit, the north pole receives darkness for about half of the year. During the time the pole is in an area of perpetual night, the polar air mass modifies a larger amount of air, spreading out and creeping southward. The leading edge of this cold air mass is called a polar front, which is a semipermanent, semi-continuous front separating air masses of tropical and polar regions. The polar tropopause corresponds to the polar air mass; therefore the "break" is located farther south during the winter.

### POLAR OUTBREAK

The term "circulation" refers simply to the movement of air relative to the earth's surface. The sun heats the earth's surface unevenly. The most direct rays of the sun strike the earth in the vicinity of the equator, thus heating equatorial regions much more than the polar regions. In addition, equatorial regions re-radiate to space less heat than is received from the sun, while the reverse is true at the poles. Yet, the equatorial regions do not continue to get hotter and hotter, nor do the polar regions get colder. The only plausible explanation is that heat is transferred from one latitude to another by the actual transport of air.

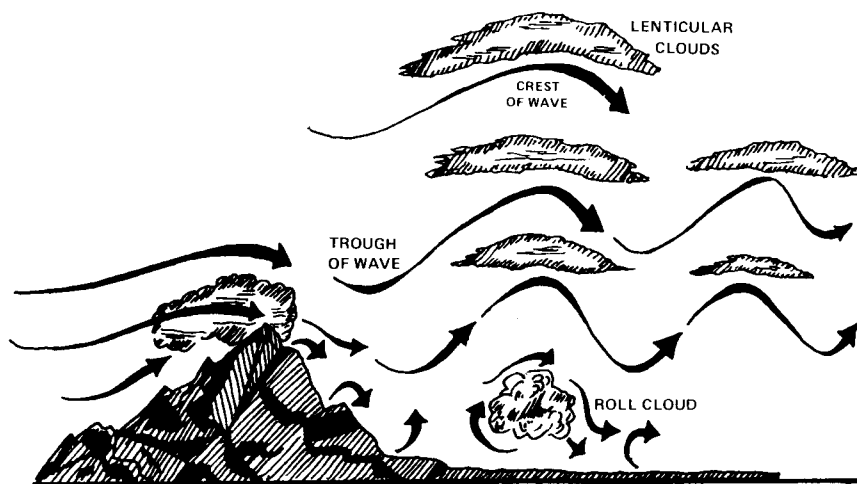
The rotation of the earth causes "Coriolis force" to modify the circulation pattern. As heated air is forced to rise, it moves northward from the Equator. It is deflected towards its right or east and by the time it has traveled a third of the way to the north pole it is no longer moving northward,

but eastward. This causes the air to pile up in the so-called "horse latitudes" (around 30° north latitude) and produces a high-pressure area.

In the polar regions a similar process is in operation, with the southward moving polar air being deflected toward the west to become an east wind. This causes the air to stagnate and form another high pressure area.

These high pressure areas create an instability in the atmosphere. In trying to regain stability the air masses begin to move.

That air mass from the horse latitudes is forced northward and is deflected toward the east to become a west wind, thereby producing the so-called "prevailing westerlies" of the middle latitudes. The cold polar air is forced to break out spasmodically in waves, which surge towards the Equator, reducing the accumulated pressure. This is called a **polar outbreak** or **cold wave**. These two air masses meet. The boundary zone where the wedge of cold polar air comes into contact with the warmer air of the prevailing westerlies is called the "polar front." This forms an almost continuous irregular polar front in all directions from the polar region. It is along this line where the cold air and warm, moist air bump together causing considerable weather throughout the United States, usually in the form of a cold front. And, mountain waves are associated with the passage of cold fronts.



**The MOUNTAIN WAVE...**  
**severe to extreme turbulence in the roll**  
**cloud area with strong up and down drafts.**

## MOUNTAIN WAVE CONDITIONS

There are three conditions favorable for the formation of the mountain wave and without which the mountain wave will not exist. These are:

1. **Wind flow perpendicular to the mountain range or nearly so, being within 30° of perpendicular.**
2. **An increasing wind velocity with altitude, with the geostrophic wind velocity between 15 and 25 knots or more near the top of the mountain, depending upon the height of the range.**
3. **Either a stable air mass layer or an inversion below 15,000 feet.**

If the air mass is too stable, or too unstable, strong vertical currents could destroy or prevent formation of the wave even if all the conditions favorable for wave formation are met.

## FAVORED AREAS

Mountain waves occur most frequently along the central and northern Rockies and the northern Appalachians.

## MOUNTAIN WAVE FORMATION

How does the atmosphere go about setting up a mountain wave? The whole airstream receives a jolt as it hits the mountain range. With unstable layers above and below, this condition sets up an oscillation where the unstable layers are flexible enough to set up a vertical motion.

When "unsaturated" air rises by forced ascension up a mountain slope, its temperature decreases at the rate of 5½°F per 1,000 feet. This cooling rate of unsaturated air is known as the "dry adiabatic lapse rate." This air beginning at sea level and 59°F would have a temperature of 4°F at 10,000 feet. Comparing this to the standard "free-air" lapse rate of 3½°F per 1,000 feet, the ambient air temperature at 10,000 feet would be 24°F. Remove the lifting action and the difference in temperature will cause the unsaturated cold parcel of air to seek its original altitude, descending on the lee side. Given the right circumstances it will then set up an undulating pattern.

Why does stable air squeezed between two layers of lesser stability favor the formation of significant mountain waves? It is convenient to employ an analogy.

Unstable air encountering a mountain can be compared to a weak, flimsy spring, which would offer little opposition to vertical motion. The lower portion of the spring would move easily up and over the mountain, yet the shock it receives would not be transmitted very far upward through the spring.

A completely stable air flow can be compared to a heavy, dense spring that tends to suppress internal vertical motion. When this heavy spring is forced over a mountain ridge, it is too strong for oscillations to be set up. A stable air mass layer or an inversion below 15,000 feet can be likened to a strong spring sandwiched between two weaker springs. With this arrangement, the strong spring would continue to bounce up and down for some time after the jolt of crossing the mountain range.

The atmosphere works in a somewhat similar fashion. Neither a completely unstable, nor a uniformly stable air flow can produce appreciable lee waves. But, stable air between layers of lesser stability is flexible enough to be set in vertical motion and elastic enough to continue that motion.

### MOUNTAIN WAVE DIMENSIONS

In talking about mountain wave flow, two dimensions are appropriate to such a discussion. These are "wave length" and "amplitude."

The **WAVE LENGTH** is a measure of the distance from one wave crest to the next, or from trough to trough. Wave length is directly proportional to wind speed and inversely proportional to stability. Lenticular clouds in successive bands downstream from the mountain mark a series of wave crests and this spacing marks the wave length. The wave length is between 2 and 25 nautical miles, averaging 8 miles in the Rocky Mountains, and extending downwind from the mountain range 150 to 300 miles. Weather satellites have observed waves extending nearly 700 miles downwind from the Rocky Mountains. While Appalachian waves are not as strong as those over the Rockies, they occur frequently, extending downwind an average of 115 miles. The wave length averages about 10 miles. Soaring flights to more than 24,000 feet have been made in Appalachian waves, and flights to as high as 20,000 feet have been recorded from New England to North Carolina.

The lee wave **AMPLITUDE** is half the vertical distance from wave trough to crest. In a typical wave, amplitude varies with height above the ground. It is least near the surface and near the tropopause. The greatest amplitude is generally between 3,000 and 6,000 feet above the ridge top. Wave amplitude is controlled by size and shape of the ridge as well as wind and stability. A shallow layer of great stability and moderate wind produces a greater wave amplitude than does a deep layer of moderate stability and strong winds. Also, the greater the amplitude, the shorter is the wave length. Waves offering the strongest, most consistent lift are those with great amplitude and short wave length.

For 17 years the world altitude sailplane record was 46,267 feet, set by Paul Bickle in the Tehachapi Wave or Sierra Wave near Bishop, California, in 1961. and these are relatively low mountains.

A wave cloud is not an absolutely sure sign of strong updrafts and downdrafts. Nor does it indicate the level at which the waves are most pronounced. The clouds merely indicate the level at which sufficient moisture is available to form them.

### TYPICAL CLOUDS

With sufficient moisture, three typical wave clouds will form:

1. The **CAP CLOUD** or **FOEHNWALL** is mostly on the windward side of the mountain and it dissipates on the lee side where the air descends, heats by compression and can absorb large amounts of moisture.
2. The second cloud type and a "sign post" of wave conditions is the **LENTICULAR** cloud. Mountain waves may or may not be marked by lenticular clouds. Lenticular clouds are lens-shaped clouds that are composed of water vapor or ice crystals, normally from 20,000 to 40,000 feet. The development of lenticular clouds depends on the humidity of the air aloft.

As the air is forced to rise, it cools by expansion to the dew point, and if sufficient moisture is present, it condenses out and moves over the crest of the wave and down the other side until the heat of compression evaporates and reabsorbs it. This forms the lenticular clouds that mark wave crests. A cross-section of the cloud form resembles a lens or almond. The waves may develop singly; but more often, they occur as a series of waves downstream from the mountains. While it is being constantly formed on one end and dissipated on the other, it takes on the appearance of a standing wave.

As many as five separate lenticular layers may stack up, one on top of the other, over the mountain range that forms them. Each one of these lenticulars is separate and distinct from the other, caused by cooling air ascending and saturating the crest, then warming as it descends to evaporate the cloud. Thus, by continuous condensation windward of the crest and evaporation leeward, the cloud appears stationary, although wind may be blowing through the wave at 50 knots or more.

With high-level moisture, only high-level lenticulars will be visible, while the strongest wave condition may exist at a lower level where there is insufficient moisture to mark its activity. The appearance of lenticular clouds merely points out wave activity, not wave intensity at any particular level.

This wave lift can extend into the stratosphere, more than 10 miles above sea level, so we can't escape wave effects by flying over them.

A common misconception is that lenticular clouds are a “signpost of the sky” indicating a 180° turn to the average lightplane pilot. It isn’t necessarily so.

3. The third cloud type is a ROLL, ROTOR or ARCUS cloud. It may form and be nearly as stationary as the lenticular. It is formed continually on the upslope and dissipated on the downslope side. This cloud, in contrast to the lenticular, is definitely a “signpost of the sky” indicating avoidance of its area.

Interaction of rising and descending air between the troughs and crests of a wave and the high velocity of the air spilling over the mountain crest like a waterfall, causing strong downdrafts, can combine with the lower velocity of air near the surface to cause the rotor. If two objects are placed together and one is moved along the surface of the other, friction results. The same thing occurs when two air currents of different velocities move along the surface of one another. Being fluid, one body of air will not move along another on a plane surface, but friction will create a mixing zone where eddies will be set up. Additionally the downdraft air can become so violent that it bends back at ground level rather than flowing away from the mountain. This violent “overturning” forms a series of rotors. While the surface winds flow back toward the mountain they are forced upward by rising terrain or by mixture with the ascending wave flow, moving away from the mountain once more. This process repeats itself, setting up a rotary action. With sufficient moisture, condensation will appear, marking the rotor cloud. A mixture of dust and debris may also be present, which forms the “textbook” description of the rotor as “a very dark, ominous-looking cloud that has a rotating appearance.”

Clouds resembling long bands of stratocumulus sometimes mark the area of overturning air. These rotor clouds appear to remain stationary, parallel the range, and stand a few miles leeward of the mountains. Turbulence is most frequent and most severe in the standing rotors just beneath the wave crests at or below mountain-top levels.

The rotor cloud moves in a rotary motion that may or may not be detected by the pilot. Many times the rotor cloud looks much like a “fair weather cumulus” or a patch of innocuous stratocumulus unless you take a closer look. Upon closer inspection, it is sometimes possible to observe fragments of the cloud being torn from the trailing edge and to see that the top of the cloud moves much faster than the base.

If any movement or rotation of the cloud edges is detected, detour the cloud area. Updrafts and downdrafts in excess of 5,000 feet per

minute have been encountered in this area! The rotor cloud will be downwind from the mountain range and will extend anywhere from the earth’s surface up to mountain-top level.

### TURBULENCE

The mountain wave indicates the possibility of turbulence, but most are gentle with only light turbulence. The air flow is laminar in the wave area and generally not turbulent. HOWEVER, BENEATH THE LENTICULAR CLOUD may be an area of SEVERE TO EXTREME TURBULENCE, which is sometimes marked by the rotor cloud.

Mountain wave turbulence is about the severest type that can be encountered. The wave itself contains some mighty lift and sink. The rotor cloud, on the other hand, contains turbulence that has been known to demolish aircraft and sailplanes in an instant!

Of all the major meteorological flight hazards, the rotor ranks near the top, producing some of the most violent turbulence likely to be encountered in the troposphere.

### FLIGHT PLANNING PROCEDURES/PRECAUTIONS

When planning a mountain flight with a wave present you should know what to expect, and plan your flight accordingly.

- \* During a period of wave development or suspected activity it’s a good idea to talk with local pilots to determine the best route and flight procedures.
- \* Check for PIREPS (pilot reports).
- \* Check SA’s (hourly sequence reports) for “ACSL” in the “remarks” section.
- \* Check to see if a cold front has passed the area of intended flight recently or if one is forecast for the duration of the flight.
- \* Generally a mountain flight during a period of wave development will present no difficulty, since the degree of stability of the air can be judged during the climbout. If the air is too rough, go back to the airport and wait it out.
- \* Visualize wave length to determine the best area to fly when your course parallels the mountains. Fly in the updraft between the trough and crest.
- \* Visualize the formation of the mountain wave. If your flight follows a course along a northwest to southeast line or a southwest to

northeast line, fly the wave as you would a front. Don't spend time flying through it at any angle less than 90 degrees. Turn perpendicular to the wave, pass through it in the least distance (if feasible due to terrain features) and proceed on course.

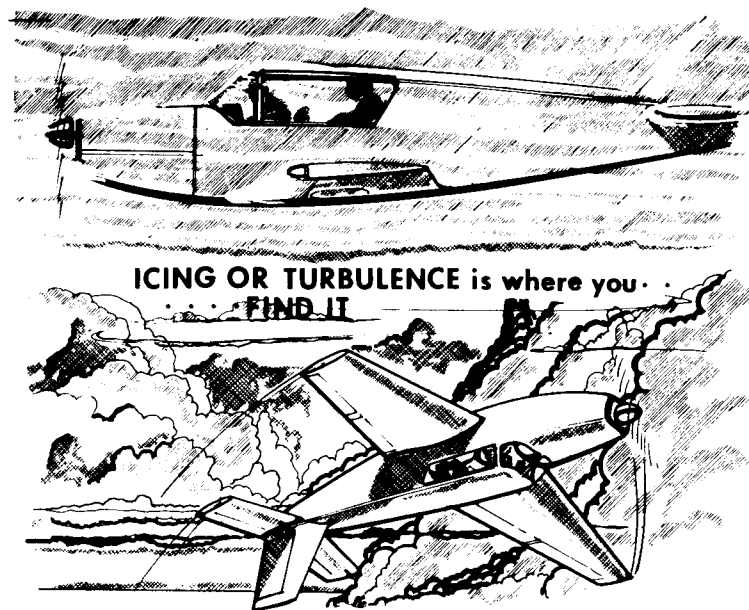
- \* Maintain a minimum of 3,000 to 4,000 feet above the mountain tops as you approach the mountain ridge. Climb to this altitude before reaching the mountains. If downdrafts are encountered that exceed the maximum rate of climb, make a 180° turn.
- \* It wouldn't be good judgment for an inexperienced pilot to attempt a flight during mountain wave conditions in an airplane that does not have a little extra margin of performance. Depending upon the height of the mountains to be flown over, this extra performance could be an airplane that will climb as little as 200 feet per minute when 3,000 feet above the highest terrain.
- \* Approach the mountain range at a 45° angle to allow a quick turn from the ridge to an area of lower terrain.
- \* Probably the most dangerous characteristic of the standing wave for the uninformed pilot beginning his first mountain flight in such a condition, is the magnitude of the sustained updrafts and downdrafts. If caught in a downdraft, speed up to get out of the area faster. This results in less altitude loss than flying at the best rate of climb or angle of climb speed. Those slower speeds prolong your exposure to the wave's effects.
- \* Normally we advocate flights early in the morning or late in the afternoon to escape the effects of local winds and density altitude. This is generally sound advice; however, there is a diurnal variation of lee waves. Early morning and late afternoon are favorable for wave formation. The middle of the day is the least likely period for waves when they are suppressed or even obliterated due to convection.
- \* Visualize the wave length, even without clouds being present, and concentrate your flight time in the updrafts rather than downdrafts.
- \* On north-south flights, cross over the mountains if necessary to fly the windward side of the mountain. Avoid the lee side if at all possible.

## AIRCRAFT ICING

### BEWARE OF MOUNTAIN IFR

Instrument pilots should beware of mountain IFR because of the high enroute altitudes required. The minimum enroute altitude (MEA) is at least

2,000 feet above the highest terrain within four nautical miles to either side of the airway in mountainous areas, but a minimum reception altitude (MRA) might require higher enroute altitudes. These high altitudes are conducive to structural icing, not only in winter, but also in summer months. In fact, the worst icing may occur during the summer months (because there are more cumulus type clouds) when the free air temperature is between 0°C and -10°C.



### AIRCRAFT ICING

If you're going to fly instruments, regardless of whether it is over the mountains or not, sooner or later you will have an encounter with ice. No matter where it happens or how much you get, it will (or should) alarm you.

Although the atmospheric conditions that produce icing are well known, some allowance should be made for the unexpected. Under what appear to be identical situations, the icing intensity can vary considerably with the passage of a few minutes' time. Weather changes, often with dramatic abruptness and sometimes with tragic consequences.

The *basic premise* of icing is that *the first traces of ice should be a warning that calls for immediate action*. When you start picking up ice, get out of it! If you sit there complacently, the consequences are like receiving a parachute as a gift...that opens on impact.

There are many variables associated with ice; however, we can make one positive statement: Ice is consistently DANGEROUS.