WEATHER TO FLY

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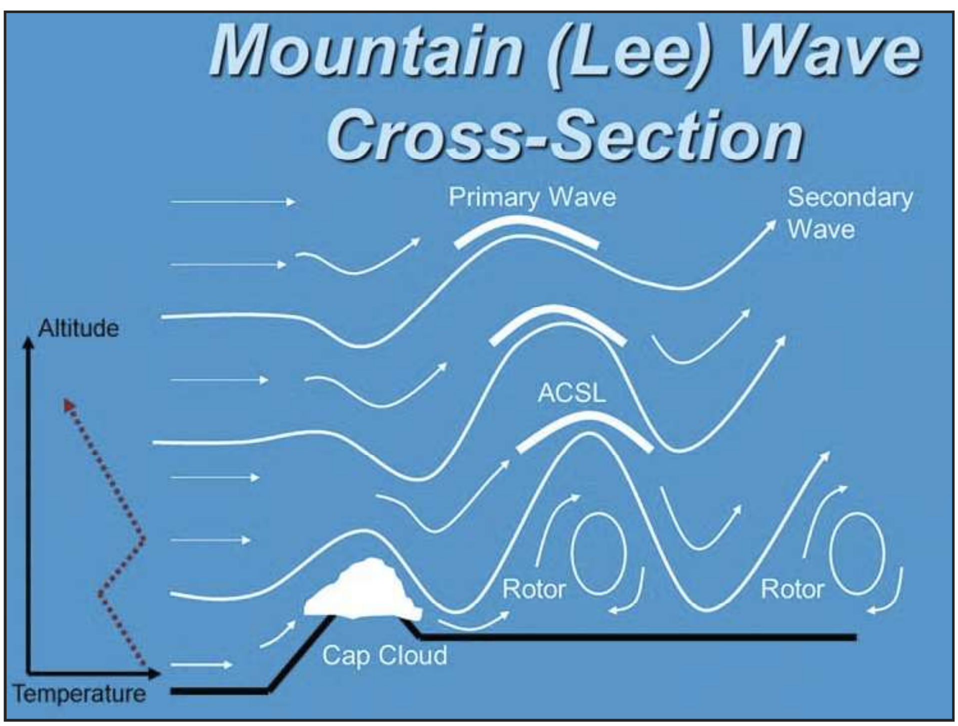
Mountain Wave Forecasting

We introduced the 'Mountain Wave' as an atmospheric lift mechanism, its conceptual model, some history on its exploration, and wave terminology in the December 2011 issue of *Soaring*. Because of frequent confusion in regard to the location of the primary wave lift zone, I emphasize that the mountain wave is a "downwind" lift phenomenon, i.e., the upward vertical motion associated with the primary wave for purposes of soaring flight is downwind of the disturbing mountain boundary to the mean wind flow.

The conceptual model of the mountain wave **[See Diagram #1: *"Mountain (Lee) Wave Cross-Section"*]** is quite sound and has been known for several decades. What has changed is the power and speed of technology to run complex mathematical equations that enable meteorologists to graph and provide visualizations of atmospheric air motion within a wave. Deferring discussion further on the physics of the mountain wave to a future article, I wish to itemize some of the "forecast rules" that have been empirically derived by pilots and soaring meteorologists. There is nothing-new under-the-sun (pun intended!) in regard to these simple rules for forecasting a mountain wave. In fact, parameters that would lead to a mountain wave were posted with a date in the late 1950s in the old Riverside (California) National Weather Service (NWS) Office of Agriculture and Fire Weather.

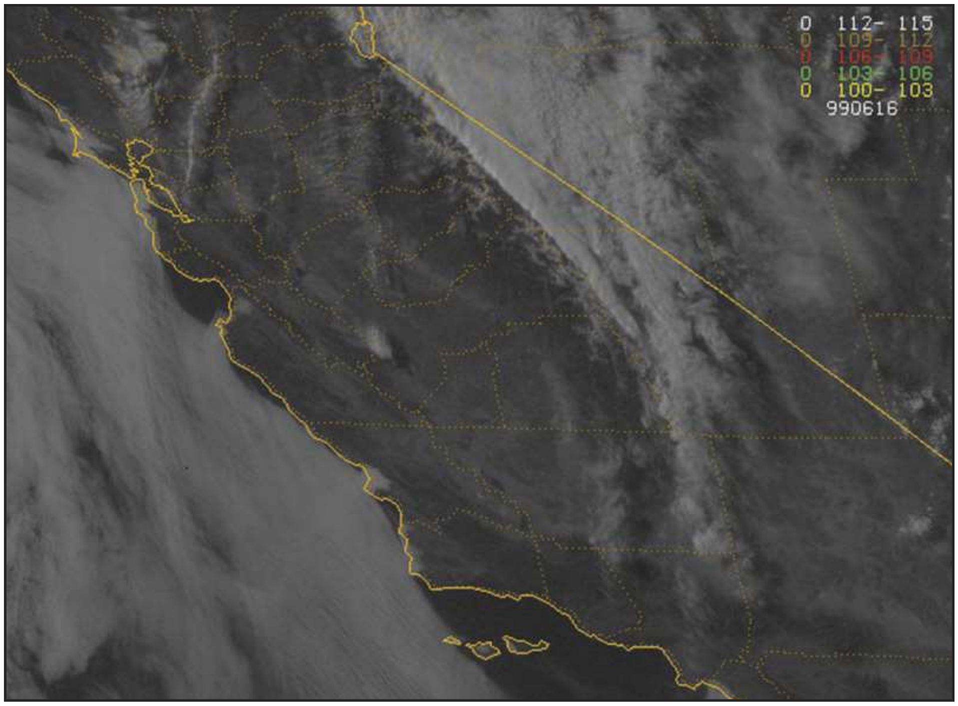
Meteorology texts are consistent in their listing of the parameters necessary for the development of a mountain wave. Physically some favorably shaped topographic feature is needed to disturb fast moving air. Typically, a terrain feature that can establish a wave is presumed to be a mountain range but it can vary to that of a single mountain peak. The minimum threshold wind speed over the top of the mountain boundary varies among textbooks but it is generally stated to be in the 25 to 30 knot range. To provide conditions favorable for a wave to exist over long distances, a long mountain range of nearly constant height aligned nearly perpendicular to the wind flow is necessary to have the air go up and over the terrain rather than flow around the disturbing boundary. Within some reference sources, the angle of the mountain range to that of the wind direction may vary up to +/-30 degrees from perpendicular for a wave to still be feasible. The shape of the mountain range is also very important for optimum mountain wave development. A shallow angle of terrain increase providing airflow uplifting is necessary up to the mountain range crest; and then marked by a steep decrease in the terrain height from that crest. The air mass wind speed needs to be sufficiently fast such that turbulent eddy wind speeds are negligible when compared to the overall wind speed over the mountain crest. Upon reaching the top of the mountain range the terrain "drop-off" leads to a katabatic wind, i.e., wind blowing down an incline. As the air descends, it rapidly warms due to compressional heating in response to the higher pressure at lower altitudes. The atmosphere's response to this heating and rapid loss of altitude in the wind flow results in a "hydraulic jump" and initiates the mountain wave. While the terrain features sufficient to develop a mountain wave are numerous around the United States, the most classic terrain feature is the "Sierra Front" along the California-Nevada border. **[See Satellite Photo: *"Full Range Sierra Nevada Wave"; 6:15 PM PDT, June 15, 1999.*]** The escarpment or rapid drop from the high Sierra Nevada and Tehachapi Mountain crest eastward to the high desert floor provides arguably the best terrain conditions for mountain wave development in the country. Established airfields such as the Minden Airport south of Reno, Nevada, or Bishop Airport, Inyokern Airport, or California City Airport in California are positioned frequently beneath mountain waves. Again, any mountain barrier can



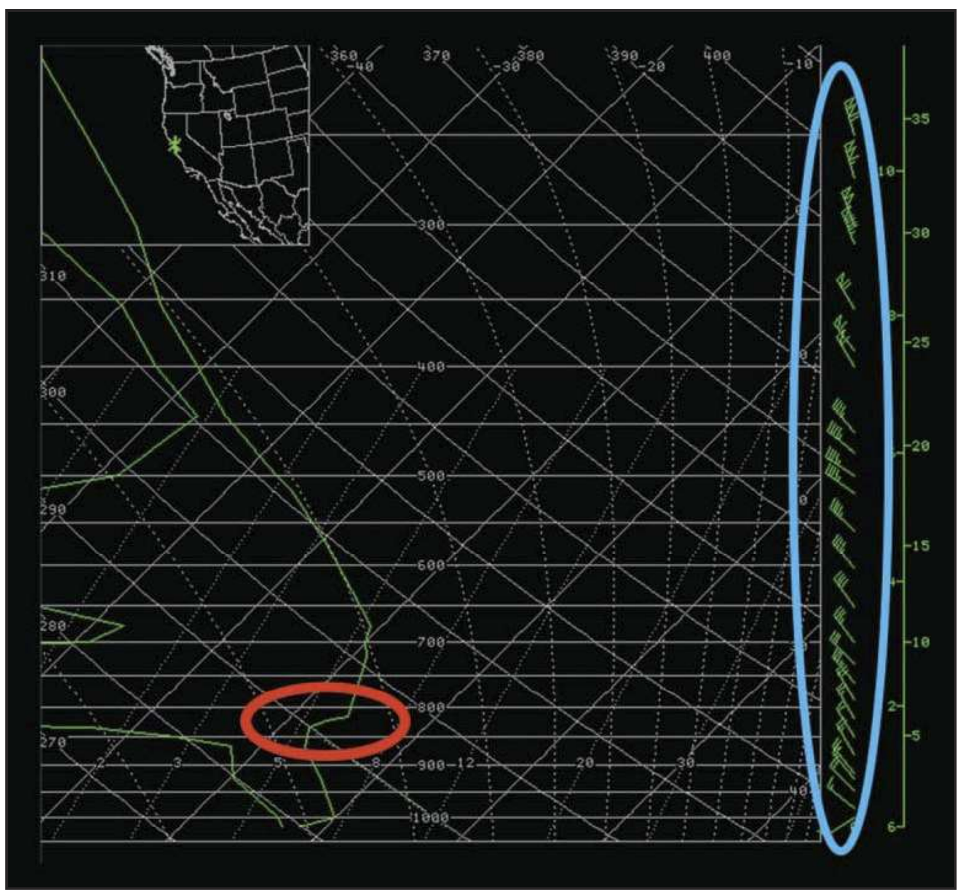
develop mountain wave action whether it is a range such as the Sierra Nevada or a single peak like Mt. Shasta in Northern California.

Intuitively, the faster the wind speed then the greater the uplift in a mountain wave. The fastest wind speeds occur in upper air jet streams (relatively strong winds concentrated in a narrow stream in the atmosphere). By definition, a wind speed of 50 knots at the 500-millibar pressure level (approximately 18,000 feet Mean Sea Level) is a minimum threshold for defining a jet stream. Despite the fastest winds speeds occurring in the jet stream, the presence of too much atmospheric uplift results in widespread cloudiness when the jet stream is directly overhead. Therefore, the best mountain wave conditions are often ahead of an approaching trough of low pressure before the arrival of its supporting jet stream, or just south of the axis of the jet stream (in the Northern Hemisphere). The presence of too much wind shear will not allow mountain wave development. Therefore, some degree of consistency is necessary in wind direction with a gain in altitude through the troposphere, the lower portion of the atmosphere, along with some degree of wind speed consistency. With less frictional influence from the earth's surface, wind speeds typically increase with a gain in altitude. **[See Diagram #2; *"Mountain Wave Upper Air Sounding"; Oakland Raob; 4 AM PST, March 16, 2001* (*blue circle around the wind speeds)*]**. This referenced upper air sounding was upstream of a large and sustained mountain wave in the lee of the Tehachapi Mountains.

It is known that "stable air" is also a necessary ingredient for mountain wave development. However, that stable air needs to be positioned in an atmospheric mid-level layer approximately at or just above the altitude of the mountain range crest or peaks. Remember that any isothermal layer (no change in temperature with a gain in altitude) or temperature inversion (temperature increases with a gain in altitude) is deemed a stable atmosphere by definition. [Referencing the ***"Mountain Wave Upper Air Sounding"***, note the ***red circle*** at a mid-level stable layer around 6,500 feet MSL]. Recalling our aviation meteorology training, there is a temperature inversion associated with any frontal passage. Therefore, the approach of a warm front or passage of a cold front as depicted on surface weather charts conveys the expected arrival or presence of some form of temperature inversion aloft due to the fronts. The presence of frontal boundaries contributes to meeting the conditions for mountain wave development when combined with terrain and other meteorological parameters.



One last issue in regard to mountain wave flying that I wish to address is that of cloud cover. If the atmosphere contains a deep layer of moist air then the likelihood of getting Visual Flight



Rule (VFR) conditions is not likely to occur due to widespread cloudiness. Aforementioned, the best mountain wave conditions are often ahead of an approaching jet stream, or just south of the jet stream axis, so that the uplift and resulting widespread cloud development associated with a trough of low pressure does not remove VFR flying conditions. If the observed or forecast atmospheric sounding, on the other hand, shows well-separated vertically spaced layers of moist air then VFR conditions may exist so that the wave can be accessed for soaring flight. The absence of moist layers and resultant clear skies does *NOT* mean that a mountain wave may not exist… only that it may be "blue" or unmarked due to a lack of cloud features. The "blue wave" is one of the most threatening of meteorological situations. Not being marked by wave cloud signatures, lenticular or roll clouds, the presence of large downdrafts on the lee side of mountains and/or the extreme turbulence associated with mountain wave rotor poses danger to an unwary aviator.

Therefore, in summary and courtesy of decades of empirical knowledge, here are some "guidelines" for the development of a mountain wave:

1) Terrain: Ideally some degree of asymmetry for a high mountain range or peak with a "flat" windward slope and a steep leeward slope;

2) Wind direction perpendicular (or nearly perpendicular) to the mountain range. Typically the range is a north-south oriented mountain range resulting in a perpendicular boundary to the mid-latitude westerly or zonal wind flow;

3) Wind direction that remains consistent in direction or only changes slightly and smoothly with an increase in altitude;

4) Wind speed that smoothly increases with a gain in altitude starting with wind speeds in the 25 to 30 knot range over the mountain range crest or peak;

5) Optimum wave development occurs close to the axis of the jet stream or highest wind speeds aloft. Minimum winds speeds at the 500-millibar pressure level (approximately 18,000 feet Mean Sea Level) are close to 50 knots;

6) A frontal inversion that provides for a mid-level stable layer close to the crest level of the mountain range or peak; and,

7) Layers of moisture rather than a deep layer of moisture over the mountain range that provide some "marking" of the wave with cloud features.

In the next issue of *Soaring*, we will continue discussing mountain waves and describe some of the physics behind the wave development.

Mountain or Lee Wave Terminology

Lee Wave – Any wave disturbance that is caused by, and is therefore stationary with respect to, some barrier in the fluid (air) flow.

Cap Cloud – An approximately stationary cloud, or standing cloud, on or hovering above a mountain peak or range crest. It is formed by the cooling and condensation water vapor within that air as it is forced to rise over the mountain peak or range (upslope/orographically formed).

Altocumulus Standing Lenticularis (ACSL) – A cloud species at the middle levels (6,500 to 20,000 feet mean seal level) of the troposphere, of which the elements have the form of more or less isolated, generally smooth lenses or almonds. The outlines of the ACSL are often sharp and sometimes exhibit brilliant spots or borders of coloration. The soaring community often will refer to this cloud type as a "lennie" and the description "pagoda cloud" is used to describe the appearance of vertically stacked ACSL clouds that have formed due to air layers of varying moisture content within a mountain wave.

Rotor Cloud – (Sometimes called Roll Cloud.) A turbulent, altocumulus-type cloud formation found in the less of some large mountain barriers, particularly the Sierra Nevada Range near Bishop, California. The air in the cloud rotates around an axis parallel to the range.

Foehn – A warm, dry wind on the lee side of a mountain range, the warmth, and dryness of the air being due to adiabatic compression upon air descending the mountain slopes.

Foehn Wall – The steep leeward boundary of flat, cumuliform clouds formed on the peaks of mountains during foehn conditions.

Foehn Gap – A Foehn gap is a cloud-free area just downstream of a mountain crest, between the cloud layers on the upstream side of the mountain range, and the lee wave (or lenticular) cloud on the downstream side.

Primary Wave – The first atmospheric wave crest leeward and downwind of the mountain range or peak in an established lee wave.

Secondary Wave (tertiary, quaternary, etc.) – A repeating atmospheric lee wave downstream of the primary wave that has resulted from airflow over a disturbing topographic feature such as a mountain range or peak.

Vertically Propagating Wave – A mountain (lee) wave that may reach all the way into the stratosphere (above 35,000 feet MSL) but has few or no secondary wave crests farther downstream.

Trapped Wave – A mountain (lee) wave that has repetitive wave crests downstream.

References:

"*Glossary of Meteorology*," Published by the American Meteorological Society, Edited by Ralph E. Huschke, copyright 1959 and corrected 1970.

"*Weather Forecasting for Soaring Flight, Technical Note No. 203*"; World Meteorological Organization; Prepared by Organisation Scientifique et Technique Internationale du Vol a Voile (OSTIV); 2009 Edition; (Mountain Wave Characteristics, detailed on pp. 40-48).