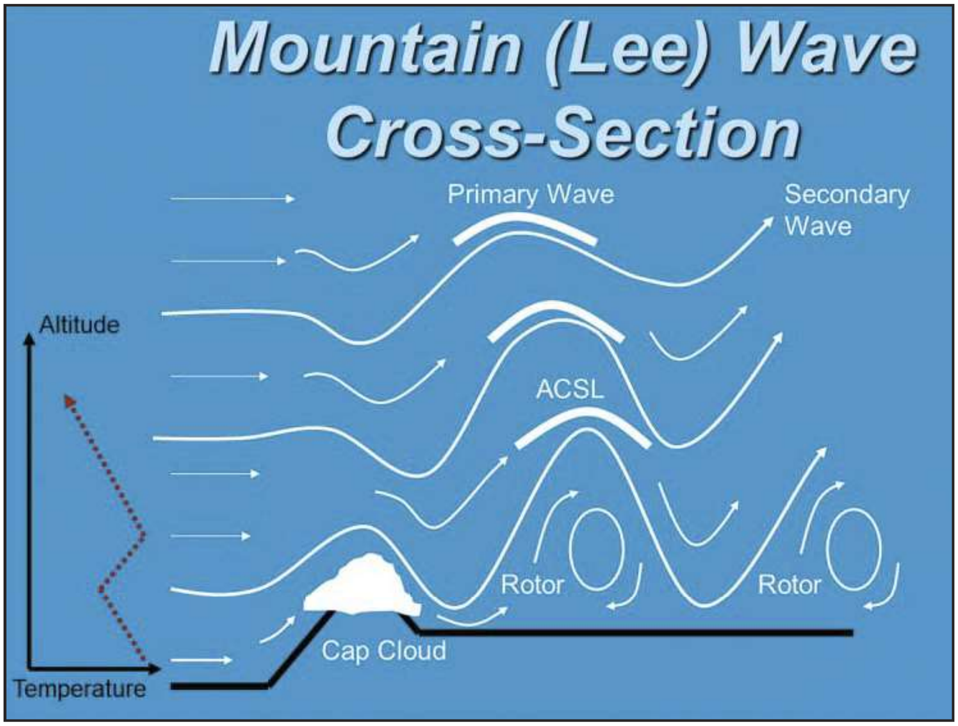
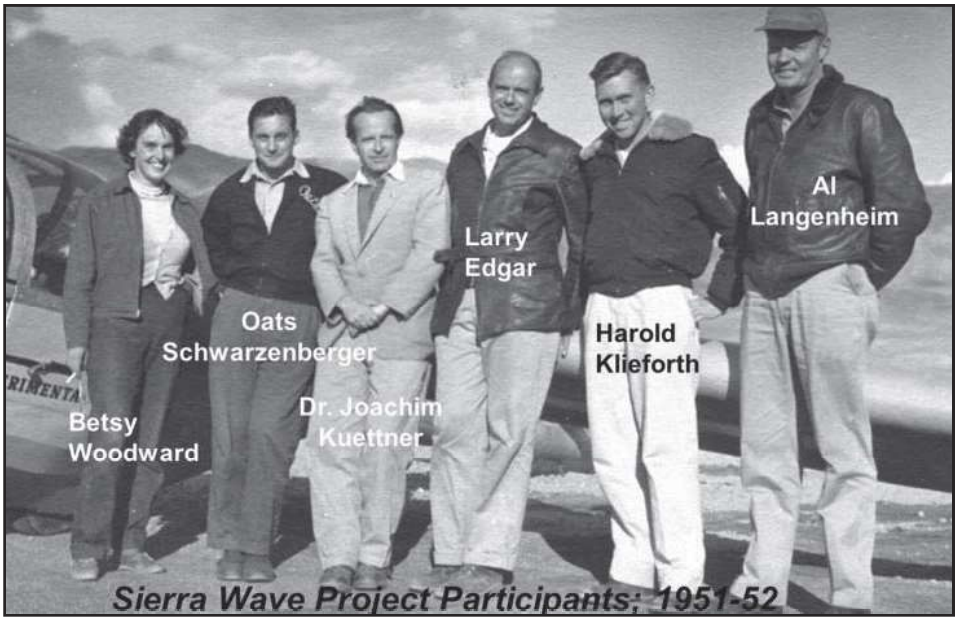


ity and atmospheric stability are crucial to the development and formation of a mountain wave. The two primary factors for development of mountain lee waves are temperature stratification and the vertical wind profile.

From a historical perspective, modern meteorology began to get a fundamentally sound understanding of the mountain wave due to the efforts and subsequent documentation of wave flights conducted around Bishop, California, under the auspices of the "Sierra Wave Project" during the 1951-1952 time period. As a young aviator and meteorologist in the National Weather Service's Reno Forecast Office in the mid-1970s I initially had no idea that a frequent office visitor from the Desert Research Institute, very unassuming, knowledgeable, kind, and quick to share his insights about Sierra Nevada meteorology, was one of the key personnel, Mr. Hal Klieforth, in that famous project. [See: *"**Sierra Wave Project Participants**."*] Since the publication of the final report on the Sierra Wave Project in 1957 and the development of computer technology, there has been a continuous gain in the knowledge of mountain waves around the world



Sierra Wave Project Participants; 1951-52 through numerous research papers. Mountain wave(s) descriptions in modern research papers are often expressed in great mathematical detail along with sophisticated model simulations of atmospheric motion that includes terrain feature interaction.

For reference, I have listed some mountain (lee) wave definitions and vocabulary [See: "***Mountain (Lee) Wave Terminology***."] Fundamentally, the development of clouds in and around a mountain wave are consistent with the same conditions needed for cloud development within the general atmosphere, i.e., a lifting action that cools air to the point where water vapor in that air condenses to its liquid state (suspended water droplets) or sublimates to its solid state (suspended ice crystals). In the mountain wave regime, clouds are often seen "capping" the airflow-disturbing mountain range or isolated peak, as "rotor" or "roll" clouds, and/or as the altocumulus standing lenticularis clouds (ACSL or "lens" clouds).

In looking at the cross-section of a mountain wave, wind speeds over the airflow-disturbing terrain must be sufficiently high to make "local" influences in the wind flow insignificant. Typically, a minimum wind speed threshold over the mountain peak or range crest for mountain wave development is in the 25 to 30 knot speed range. The wind direction should be within 30 degrees of perpendicular to the orientation of the mountain range. Because the mountain wave exists as a "standing" wave in the atmosphere, the cloud features remain stationary over a geographic point. However, the wind speed through the wave is anything but stationary. Since a mountain wave can be vertically propagating, wind speeds at the higher altitude within the wave can seasonally approach those of higher speed jet streams, i.e., often in excess of 120 knots. A lenticular cloud develops in the

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.

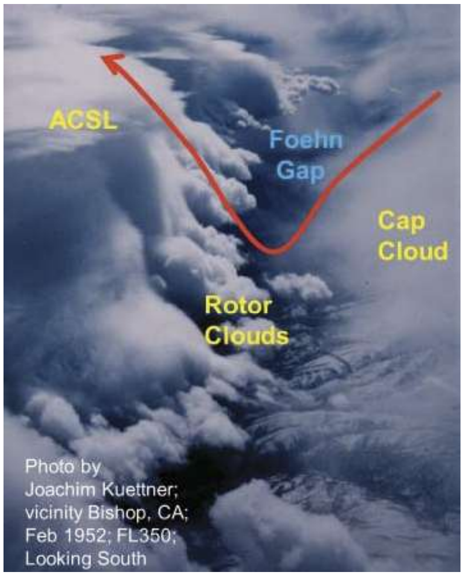


Photo by Joachim Kuettner; vicinity Bishop, CA; Feb 1952; FL350; Looking South area of rapidly rising air on the upwind side of the wave crest. With adiabatic cooling, water vapor within that rising air condenses or sublimates to visible moisture (cloud). The laminar flow in the wave keeps the cloud quite stratified but the cloud depicts the shape of the airflow over the wave crest, thus the lens shape. After crossing the peak of the wave crest, air begins a descent on the downwind side of that wave crest. Now undergoing compressional heating with descent into the higher pressure of lower altitudes the air warms enough to evaporate the visible moisture (water droplets or ice crystals) that had formed the lenticular cloud. Again, the cloud may appear stationary over a geographic point on the ground but the air is moving with high speed through the cloud.

Two types of flow mark the airflow within a mountain wave; turbulent and laminar. The rotor region is turbulent with rapid changes in both speed and direction of the airflow across the region. Typically, the rotor altitude is near the altitude of the upstream terrain crest. The dangers of the rotor region for pilots of all aircraft categories is two-fold, the existence of severe to extreme turbulence and the inconsistency of wind direction and speed in the rotor region due to turbulent eddies. Typically above the altitude of the upstream mountainous terrain or peak, the airflow in the lee wave transitions to smooth, laminar flow. Although the airflow may be laminar, wind speeds are high. Significant wind correction angles and high-indicated airspeeds are necessary for sailplanes to remain in regions providing upward motion, i.e., the upwind side of the wave crests.

One of the frequent misconceptions in regard to the mountain wave is that it develops and propagates *directly vertical over* the airflow-disturbing mountain range. This is not the case. The mountain wave is a ***downstream*** lifting phenomenon caused by an upstream mountain range or peak interacting with airflow! The reason for the misconception by Student Pilots is understandable. In a deep, vertically propagating lee wave, the wave crest tilts upwind with an increase in altitude. This upwind tilt of the primary wave crest can result in ventricular clouds marking the location of the primary wave crest at that high altitude and over the disturbing terrain thousands of feet below. A pilot flying in the lee wave, without understanding the proper conceptual model of the wave, could mistakenly assume that he is flying in some form of vertically propagated ridge lift.

Within the mountain wave regime, the cap cloud is formed due to cooling in upward vertical air motion akin to ridge lift over the airflow-disturbing mountain range or peak. Likewise, the descent of air on the downwind side of the mountain range results in compressional warming and the subsequent evaporation of the cap cloud. A Foehn Wind refers to this warming, drying air descending from higher terrain. The often impressive "wall" of clouds capping a mountain range as seen looking upwind from a downwind location is referred to as the Foehn Wall and the cloud-free area between cap clouds and leeward rotor and/or lenticular clouds is the Foehn Gap [See: ***"Mountain Wave Foehn Gap"***]. Having described the mechanism for formation and location of clouds in a mountain wave, sufficient air layer moisture is a necessary for any wave cloud development. In the absence of adequate air layer moisture and/or insufficient cooling during any wave lifting process, a mountain wave can still exist but with no visible moisture to mark wave features, i.e., no clouds! Due to severe-to-extreme turbulence in the vicinity of the wave rotor and large downdrafts downwind of the airflow-disturbing mountain range, a "blue" or cloud-free wave is extremely dangerous to the unwary aviator.

The conceptual model of a mountain (lee) wave works well for soaring flight. Like water flowing over smooth rocks in a stream bed, the fluid we know as the air in the atmosphere oscillates like the water waves downstream of those streambed rocks. With visualization of the wave conceptual model, the soaring pilot can use the uplift side of the rotor rotation thus transitioning to the lift in the laminar flow on the upwind side of the mountain wave crest. In the next issue of *Soaring*, I will show more examples of mountain waves and discuss some of the physics behind the wave development.

References:

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

"*Investigation of Mountain Lee Waves and the Airflow over the Sierra Nevada. Final Report*", Holmboe, J.R., and H. Klieforth, 1957, Department of Meteorology, UCLA, Contract AF 19(604)-724, 283 pp.

"*Stalking the Mountain Wave*", Published by the Alberta Soaring Council, Written and compiled by Ursalu Wiese, copyright 1988.

"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).

Acknowledgments:

"National Landmark of Soaring" (NLS) Program, specifically NLS #12, "Sierra Wave Project," Bishop Airport, California.