Mountain Wave Activity Over the Southern Rockies

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Introduction

Mountain waves are stationary or standing atmospheric waves which form above or on the lee of mountain barriers. These waves are often associated with turbulence and commonly cause problems for aircraft pilots. In the presence of these waves, aircraft can experience sudden drops in altitude resulting in a hazardous situation. Because of the mountains in and around the Albuquerque airspace (ZAB), mountain waves are a common occurrence and aviation hazard. In this study, data from 24 mountain wave events were examined to document the synoptic regimes and formation criteria associated with mountain waves within the ZAB airspace. Major goals of this study were to: 1) assess the formation criteria described in several references and, 2) to establish predictable mountain wave parameters.

Background Information

Topographic barriers are preferred areas for the generation of mountain waves. Mountain waves form in stable environments when the winds throughout the middle troposphere are reasonably strong, at least 25 knots, with a flow that is nearly perpendicular to the barrier. Mountain waves can be created by terrain of varying height, but the best type of wave generator is elongated terrain with a smooth surface. Thus, short cone-shaped hills are not good generators. Fig. 1 illustrates terrain over Arizona, New Mexico, southwest Utah and Southern Colorado. This region has a number of areas with mountainous terrain, particularly north-to-south barriers for which prevailing west winds are perpendicular (Reichman, 1972).

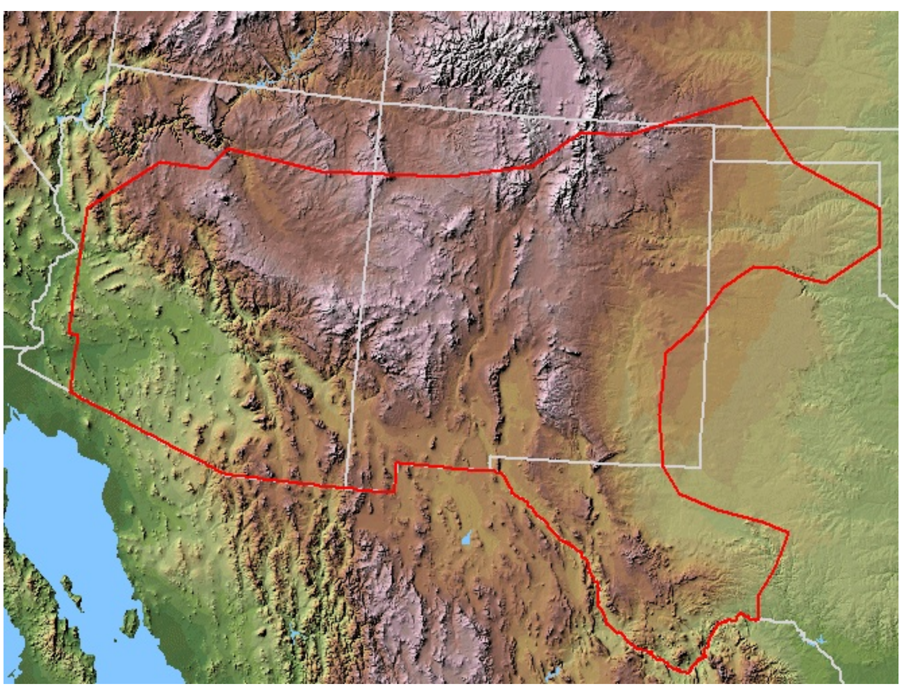

Figure 1. Terrain within and near the ZAB airspace (designated by red border).

Depending on atmospheric parameters, two types of mountain waves can develop - trapped (or lee waves) and vertically propagating higher altitude waves. Fig. 2 illustrates several of the features associated with mountain waves.

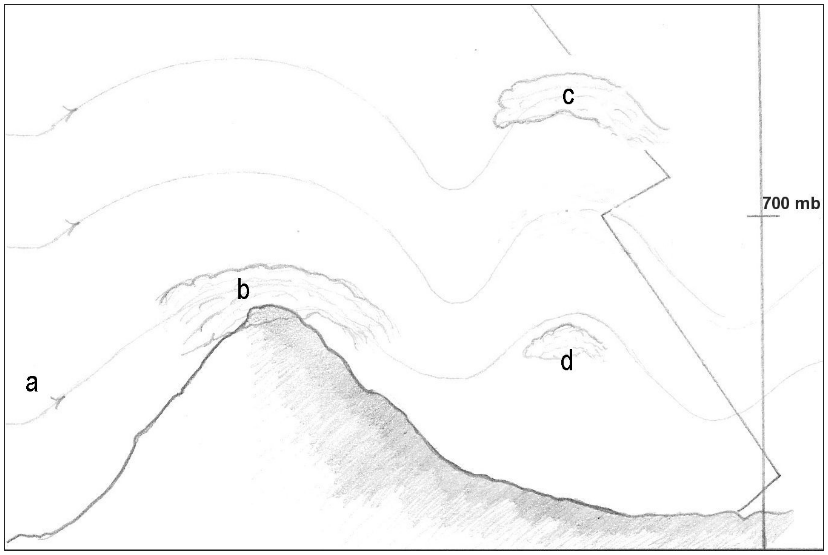

Figure 2. Features associated with a mountain wave.

In a mountain wave situation, air that flows up the windward side of the barrier (**a**, in Fig 2) has a relatively smooth, or laminar, flow (Department of Transportation, DoT,1975). When the fast-moving flow crosses the ridgeline, it is displaced vertically, then downwind of the ridge, it accelerates back to its original position, causing waves on the lee of the mountain (Reichman, 1972). The waves remain nearly stationary while the winds blow rapidly through them (DoT, 1975). With sufficient moisture, a cap cloud (**b**) will form over the barrier. Crests of standing waves may be marked by stationary, lens-shaped clouds known as standing lenticular clouds (**c**). Mountain lee wave activity strengthens the shear, promoting the development of gravity waves. The waves can repeat downwind (Reichman, 1972) and may extend 100 miles or more downwind from the barrier (DoT, 1975). These waves are also referred to as trapped waves. Under the lee wave exists an area called the rotor (**d**). Here the wave conflicts with the undisturbed normal air below and causes a tumbling or rolling of air (Buck, 1978). If the lee of the mountain is steep then rotors are very likely to form and produce violent turbulence. The rotors will sometimes appear as small scud clouds and may sometimes seem benign. Like the cap clouds, lenticular and rotor clouds can be indicators or mountain waves but form only when there is sufficient moisture for condensation. The oscillation associated with the formation of mountain waves occurs when the atmosphere is relatively stable, and conditions are favorable when a layer of stable air is located just above the barrier, often around 700 mb or 10,000 ft MSL in the ZAB airspace.

While trapped waves remain in the lower layers of the atmosphere, generally below 25,000 ft, propagating waves tilt upward reaching levels close to the tropopause (COMET, 2004). The horizontal extent of these waves is generally diminished (Lester, 1994).

Thermals can prevent waves from forming or can force them to dissipate. If the countryside in the lee of the barrier is flat, thermals may form in the same place rotors are possible. As the laminar-wave flows over the thermal area it may increase in amplitude and continue for a longer period than without a thermal. As night falls the waves can continue another one or two hours. It is within that two hours those conditions can develop into stronger waves before subsiding (Reichman, 1972).

Methodology

During the period from 1996-2004, data from 24 mountain wave events were collected for the area of northern Arizona, southern Colorado, and northen New Mexico. One of the events spanned a two-day period. It is not to be assumed that the 24 cases used in this study were the only instances of mountain waves in the area of study. In fact, additional events undoubtably occurred during these years. Pilot reports, or PIREPs, were used to identify the events. For an event to be selected for this study, the mountain wave had to first be verified by two PIREPs and then confirmed by the air traffic controller supervisor for the area. If more than three PIREPs were collected, then the confirmation by the supervisor was bypassed. Isolated reports of mountain wave activity were not considered. Instead, only events which occurred over a larger area in northeastern Arizona, southern Colorado, and northern New Mexico were considered. Next, there had to be sufficient time for CWSU personnel to collect and archive the necessary data, including the PIREPs, surface and constant pressure maps, profiler data and soundings.

Table 1 lists the events examined for this study. Cases are listed by month, with no events documented during the months May through October. The distribution of the cases in the table, with the most cases in January and December, reflects the climatology of these events documented in studies such as Julian and Julian (1969). Because wind speeds of at least 25 kts are generally required for mountain wave formation, the cold season months when wind speeds are strongest have the highest occurrences of mountain waves.

Table 1. Dates of Mountain Wave Events

January	February	March	April	No Events May through October	November	December
17 Jan 97	19 Feb 99	17 Mar 96	29-30 Apr 97		8 Nov 02	5 Dec 96
18 Jan 98	26 Feb 99	24 Mar 98	17 Apr 02			10 Dec 96
19 Jan 98	25 Feb 00	1 Mar 02				21 Dec 96
9 Jan 00	2 Feb 03					27 Dec 97
29 Jan 01						07 Dec 03
12 Jan 03						13 Dec 03
15 Jan 03						15 Dec 03

Three publications were reviewed to compile a list of formation criteria. The publications included *Turbulence Forecasting* by Mike Strieb, *Aviation Weather* by Peter Lester, and Aviation *Weather for Pilots and Flight Operations Personnel*, published by the Department of Transportation. Additionally, criteria described in a mountain wave web module produced by COMET® (Cooperative Program for Operational Meteorology, Education and Training) was also used. Complete references are listed in the Bibliography. These references describe several techniques used for forecasting mountain waves. The mountain wave events listed in Table 1 were examined using the criteria found in the references.

In the oldest reference by the Department of Transportation (DoT, 1975), it is suggested to anticipate positive mountain wave turbulence when strong winds of 40 kt or greater blow across a mountain or ridge and air is stable. The COMET® web module also states that mountain waves form above and downwind of topographic barriers when strong winds blow with a significant vector component perpendicular to the barrier in a stable environment.

Streib (1991) documented a number of criteria necessary for mountain generated moderate to severe turbulence at low levels including:

- a temperature difference across the mountain range of at least five degrees C (with warmer air to the lee of the mountains)
- a temperature gradient of 5 degrees C in 150 nm at 850 or 700 mb
- one of the following is needed on the lee side of the mountains - sharp warming surface, gusty surface winds, blowing dust to 20,000 ft, rapidly falling pressure, a rotor cloud or lenticular clouds
- Wind speeds of 30 knots or greater at barrier height
- Wind speeds of 50 knots or greater at 500 mb (for severe turbulence)

Criteria obtained from Lester(1994) include:

- the conditions for mountain wave and clear air turbulence are more favorable when a jetstream is present over a mountain area, and
- turbulence associated with the lee wave region is generally strongest within 5000 ft of the troposphere.

Profiler data, PIREPs, surface plots, and soundings were used for wind information, including speeds at critical levels, surface gusts, and reports of blowing dust. Map analyses were used to determine wind patterns, synoptic regimes and jetstream location..

Results

For all cases examined in this study, the wind has a westerly or near westerly component. While it is possible to generate mountain waves from east winds, no such cases were observed. Figure 3 was produced by examining wind data from profilers and soundings to determine a "typical" distribution of winds. The westerly component is clearly illustrated. Wind speeds near mountain top level, about 10,000 ft MSL or 700 mb, range from 10-15 knots across the south to 20 to 40 kts across the north. Trapped lee waves are commonly produced by wind speeds which increase with height.

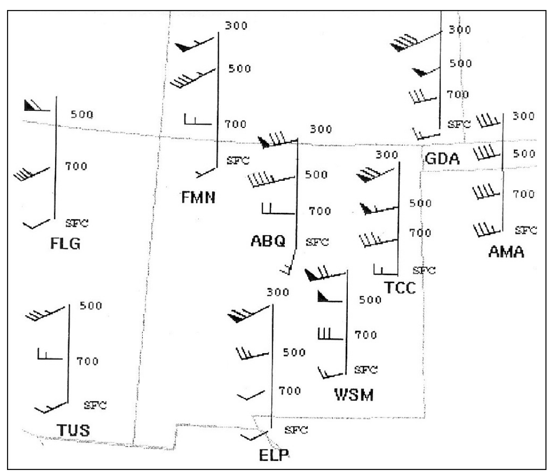

Figure 3. An example of the vertical distribution of winds obtained from profilers and soundings for the study area.

In the DoT publication, it is suggested to anticipate positive mountain wave turbulence when strong winds of 40 kt or greater blow across a mountain or ridge and air is stable. According to Reichman (1972), only 15 kt is needed, but increasing above the crest. In the 24 cases studied, the winds at 10,000 ft or 700 mb were on average near 30 kt. In all cases, an increase with height was noted.

Soundings from Flagstaff, Albuquerque and Amarillo were used to look for a temperature change at 700 mb. The five-degree change noted by Streib (1991) was not identified in any of the events. In all but three events, the average temperature difference about a 1 degree change over 150 miles.

Surface observations indicated somewhat uniform temperatures across northern New Mexico through the events, so sharp warming surfaces were not evident. However, the surface observation network across New Mexico is rather sparse, and the observation sites are at a distance from the mountain. In only one case (January 27, 1998) a temperature difference of 30 degrees existed between Alamosa, CO and Clayton, NM. Gusty surface winds were very common. In cases with surface winds less than 10 kt, profiler data indicated that the layer immediately above the surface had winds near 30 kt. The collected PIREPs did not document blowing dust to 20,000 ft but in at least 3 cases it was reported to be present between 10,000 and 10,500 ft.

According to Streib (1991), for a forecast of severe turbulence, winds greater than 50 kt should be present at 500 mb. In 19 of the cases, wind speeds at 500 mb were equal to or greater than 50 kt. He also states that rotor clouds and altocumulus standing-lenticular may be present. Surface reports never indicated these types of clouds. Las Vegas, New Mexico is the closest observing site on the lee of the mountain chain, and ASOS observations would not specify these types of clouds.

Lester (1994) noted that turbulence associated with lee waves is likely to occur within 5000 ft of the tropopause. This happens because the winds reach maximum speeds near the tropopause with vertical shears above and below that level. Five of the 24 events lacked tropopause data due to radiosonde failure. On the remaining 19 cases, the height of the tropopause averaged near 220 mb, which is about 37,000 ft. In Fig. 4, the most frequently reported PIREP altitudes from the 24 cases are plotted. Most of the activity was reported to be from 29,000 to 41,000 ft or in most instances within 5000 ft of the tropopause. Some of the activity was found to be above the tropopause where winds were still near 90 kt. In all but two cases the wind was greater than 50 kt at 300 mb. In three cases, turbulence was reported from 9,000 to 16,000 ft, possibly indicating a trapped lee wave event.

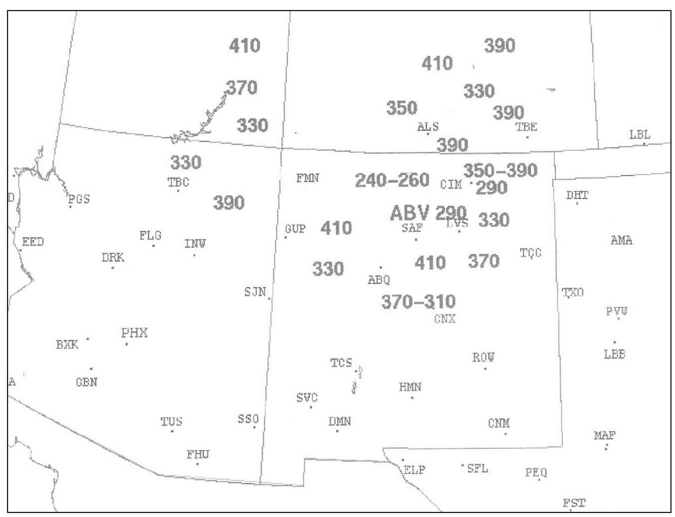

Figure 4. Most numerously reported altitudes of PIREPs reporting moderate or severe turbulence.

The conditions for mountain wave and clear air turbulence are more favorable when a jetstream is present over a mountain area (Lester, 1994 and COMET®). In 19 of 24 cases, the jet was over or in the vicinity of where the mountain wave activity was reported.

Because the formation of mountain waves depends of the stability of the atmosphere and the vertical profile of the wind, it was determined that these waves can develop within a variety of synoptic regimes. The weather pattern most common in these events (11 cases) was northwesterly flow over northern New Mexico, with a ridge situated to the west. Three cases were associated with southwesterly flow ahead of an approaching trough. Westerly flow was present in 10 of the cases, associated with passage of a trough, a weak ridge with the axis over New Mexico, or zonal flow. Figure 5 illustrates examples of the three common regimes associated with mountain waves. For the three cases, the pressure pattern at the 700 mb level and the 12Z Albuquerque sounding are shown. Note the stable layer near 700 mb.

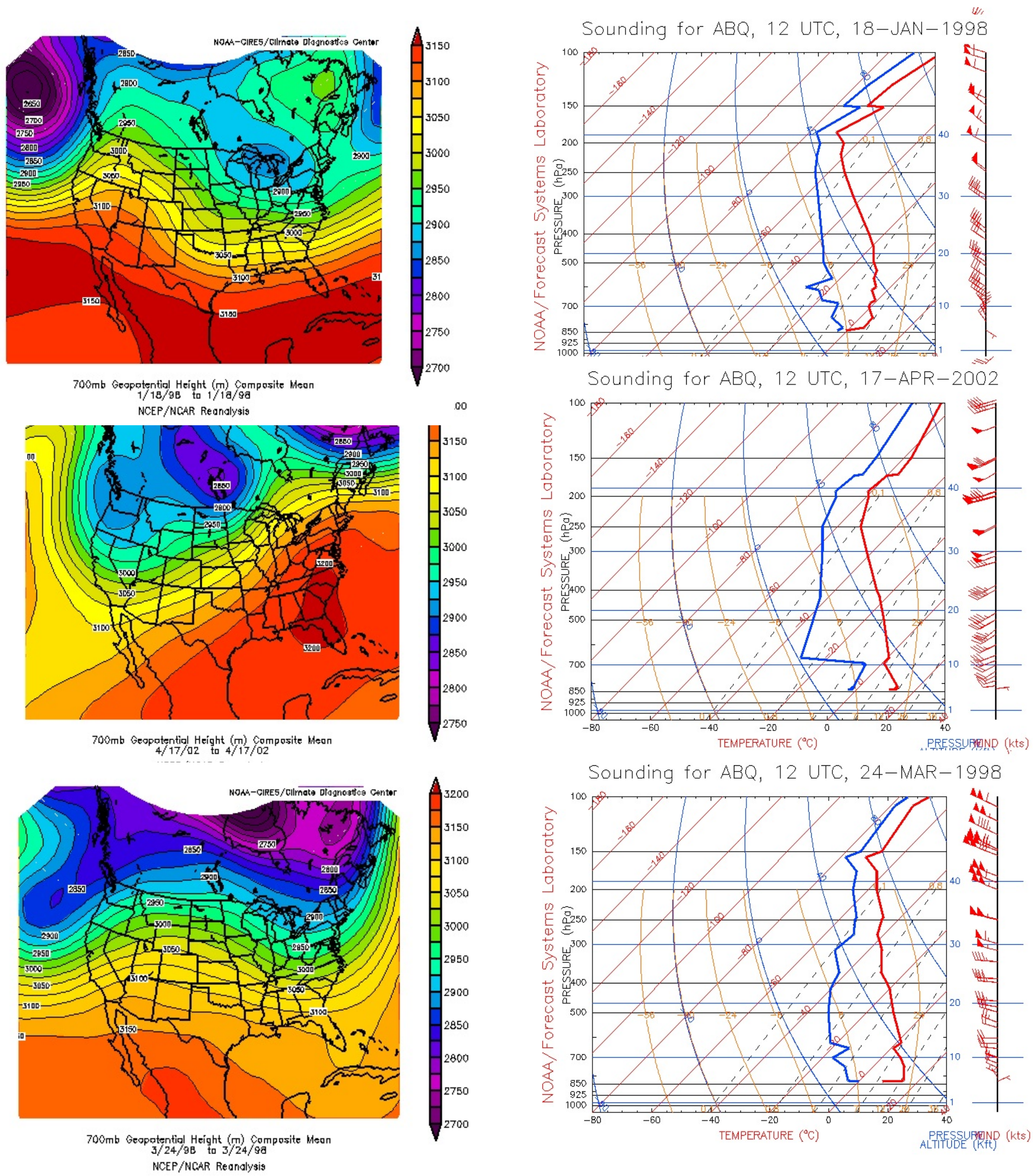

Figure 5. 700mb height and ABQ 12Z soundings for 3 events.

Conclusions

In all of the events used in this study, PIREPs had indicated mountain waves across the northern portion of the Albuquerque airspace (ZAB)in northern ZAB, or in southern Colorado, just north of the ZAB airspace. The data collected during 24 mountain wave events was examined to determine if criteria found in published studies were evident.

This study relied heavily on PIREPs to identify cases of mountain waves. It was noted that this method of identifying cases is not thorough, and many mountain wave events likely were undetected by this method. In a study by Kelsch and Wharton (1996) it was stated that PIREPs are subjective and are a function of a plane's characteristics. Additionally, air traffic controllers might pass PIREPs on to supervisors, but then may not be relayed any further. Finally, on days for which turbulence has been forecast, pilots may avoid the turbulent area and no PIREPs would be reported. It is not possible to estimate the percent of all mountain wave events identified by this method. Clearly, a different set of cases may have resulted in some different results.

However, some interesting results which can be used to anticipate mountain waves over the ZAB airspace were obtained. All referenced studies indicated that the wind should be perpendicular, or nearly perpendicular to the mountain range, with speeds of at least 30 kts near the top of the barrier. This was true for all cases. Wind speeds greater than 50 knots at 500 mb were related to gusty surface winds. In the majority of the cases, the mountain wave was reported within 5000 feet of the tropopause. Also, the jet stream was in the vicinity of the mountain wave in over 50 percent of the cases. The atmosphere was stable in all cases, and in over half of them, the Albuquerque sounding taking prior to the report had a defined stable layer at or near 700 mb. These criteria are now being used at the CWSU to anticipate mountain wave activity.

Additional On-line Resources

More information on mountain waves can be found on-line.

Satellite imagery from one of the cases in this study (24 March 1998, bottom row of Fig. 5) can be found on the web site of the Cooperative Institute for Meteorological Satellite Studies, http://cimss.ssec.wisc.edu/goes/misc/980325.html

The COMET® program has produced a web-based modules on Mountain Waves and Downslope winds, http://meted.ucar.edu/mesoprim/mtnwave/index.htm

Finally, a review of material referenced in this paper is available in:
Lester, Peter, 2003: Mountain Lee Waves: http://www.met.sjsu.edu/~lester/part3.html

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Acknowledgments

Maps in Fig. 5 were produced at NOAA's Earth System Research Laboratory web site, http://www.esrl.noaa.gov/psd

Soundings in Fig. 5 were produces at ESRL's web site, http://www.esrl.noaa.gov/raobs

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