Satellite Wave Observations used as an Aid to Wave Soaring

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Abstract

Wave cloud patterns photographed by satellites are used as a new tool for the forecaster in improving wave forecasts for soaring. Wave patterns photographed over mountain areas of the United States and other parts of the world are used including photographs over areas on dates when soaring flights were made. The present status and availability of satellite wave photographs are discussed including future prospects for development and relaying the data in the form of useful accurate forecasts to the soaring pilot before and during flight.

1. Introduction

The aviation forecaster who must attempt to predict the occurrence of waves to the lee of mountains is faced with a difficult task. The nature of airflow over mountains even of simple shape may be very complicated although the observational experience and understanding built up over the last two to three decades represent considerable progress on the subject. The formulation of a reliable and easily applied forecasting system is not yet possible. However, it is possible to provide helpful advice to pilots even though the flow above mountains cannot be predicted in quantitative detail. In common with most aspects of forecasting it is necessary to weigh the probabilities suggested by all the relevent evidence and come up with the conclusions which seem most likely.

2. Application of current theoretical and observational results

Profiles of Wind and Static Stability

The occurrence and characteristic of mountain (lee) waves are determined by the profiles of wind and static stability produced by the airstream flowing across suitable mountainous terrain. This has been show both in theories such as those of Scorer (1), Kuettner (2) and Corby (3) and in the observations obtained in field investigations.

The presence of a jet stream with its high wind speeds and strong vertical wind shear is an important factor in the occurrence of strong waves. This was pointed out by Colson in 1954 (4). In a study made by the author in the Appalachian mountain area in 1962 (5) eighty percent of the waves reported by conventional aircraft were within 200 miles of the jet stream.

Types of Observations

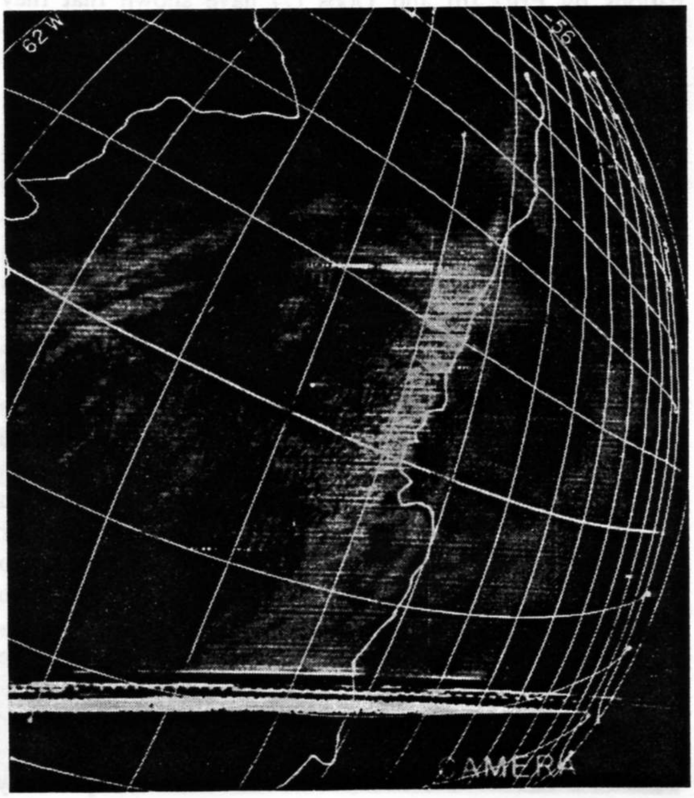
We know that lenticular clouds, if correctly interpreted as such, are reliable evidence of the existence of mountain waves in an airstream. Reports of lenticular clouds from the ground and by pilots are of value for forecasting especially as very little positive data on waves reach the forecaster. Frequently pilots of powered aircraft encounter the vertical motions produced by waves when lenticular clouds are visible although these same motions will occur without clouds whenever adequate moisture is lacking.

We now have a new capability in wave cloud observations. Since the creation of the weather satellite we can now observe spectacular wave patterns in clouds taken from great altitudes above the earth. From observations taken at the ground alone, it is difficult, if not impossible to observe organized patterns of clouds which cover near 100 miles or over in horizontal extent. In fact we can have a broad area of waves reported by a Tiros satellite and not one report of a wave type cloud made by a ground observer over the same area.

3. Satellite wave observations used as a new tool for the mountain wave forecaster

Since the advent of Tiros I in 1960, photographs of entire wave cloud patterns have been observed over the United States and other mountainous areas of the world. Investi-

Fig. 1. Wave Cloud Pattern in the lee of the Andes Mountains, as seen by Tiros I at 1738 GMT on April 18, 1960. Relatively uniform bright band, oriented N-S, is over the Andes



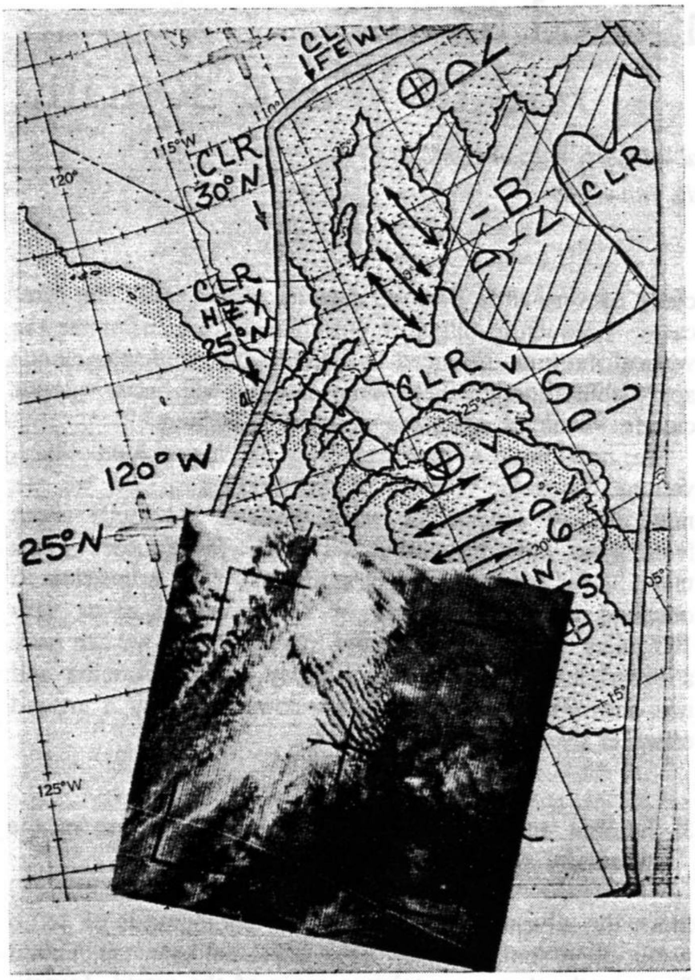


Fig. 2. Wave Cloud Pattern over northern Mexico and southwestern U.S. Taken by Tiros VI at 1710 GMT on Nov. 15, 1962

gations by Fritz (6) and Döös (7) have shown that they are produced by the usual hydrodynamical and thermodynamical processes as previously indicated in the literature.

On April 18, 1960 Tiros I photographed a wave pattern over the Andes Mountains as shown on figure 1. The relatively uniform bright band orientated N-S, is over the Andes and represents uniform cloudiness and some snow over the mountains. To the lee of the mountains a remarkably regular and widespread wave pattern appeared in the clouds. The wave pattern extended about 250 miles in a N-S direction and about 200 miles downwind from the mountains. The measured wavelength of the cloud pattern, although not exactly the same everywhere, was about 8 statute miles. The wind was from a southwest direction as shown by a radiosonde station just to the west of the mountains and increased fairly uniformly with height from about 20 knots near the surface to about 100 knots at a height of 30 000 feet. The temperature decreased at a rather uniform rate from about 17 degrees C. near the surface to about — 50 degrees C. at a height of 30 000 feet. With these distribution Döös found theoretically that the computed wavelength should be about 8 statute miles, in close agreement with observation.

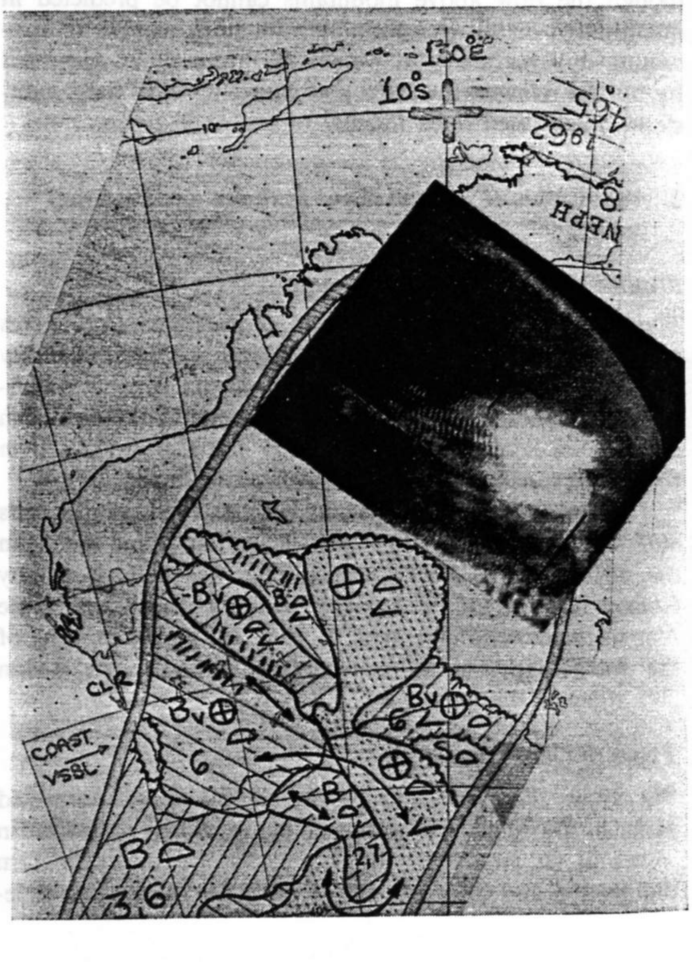
Another wave cloud pattern (figure 2) observed over northern Mexiko and the southwestern United States by Tiros VI on November 15, 1962 shows an exceptionally well defined area of waves. The wave clouds are to the lee of the mountains that extend along the western part of Mexiko. They extend for about 240 miles downwind and 200 miles parallel with the waves.

A third extraordinary wave pattern is shown on figure 3. This photograph was made by Tiros VI on October 20, 1962 while passing over Australia. The wave clouds in this picture extend for about 420 miles downwind and 350 miles in a direction generally parallel with the waves. The waves are to the lee of the group of mountains in the general area of south central Australia. There are several ranges over the area and there seem to be several different wave systems downwind from the area of general cloudiness over the mountains.

More recently in 1963 and 1964 several Tiros photographs were taken over the United States on days when wave soaring flights were made. Of course this was unknown to the sailplane pilot or to a weather forecaster until much later.

Figure 4 shows a remarkable wave pattern made by Tiros VII on June 6, 1964 as it passed over the state of Nevada in the western part of the United States: On this date a soaring pilot released over Reno, Nevada at 6600 feet, lost about 300 feet, then flew to 23 500 feet for a gain of 16 900 with a total flight time of 3 hours and 10 minutes. The small dot on the nephanalysis and on the Tiros photograph at approximately 39.5°N and 119.5°W indicates the area where the flight was made. This is just to

Fig. 3. Wave Cloud Pattern over Australia taken by Tiros VI at 0721 GMT, Oct. 20, 1962



the lee of the Sierra Nevada mountains in California. The wave clouds extend about 400 miles downwind and 330 miles along the waves. On February 5th of this year Bruce Beebe released in a wave over Mindon, Nevada at 10 000 feet and flew 250 miles to Elko, Nevada in 5½ hours. His maximum altitude was 24 000 feet.

Other flights have been made on days when Tiros wave clouds were photographed. On October 31, 1963 two sailplane flights were made from Sugarbush, Vermont when Tiros VII passed over and photographed the wave clouds. On Novembre 14, 1964 a sailplane flight was made at about the time Tiros VII passed over.

To show waves in more detail figure 5 shows a blowup of a Tiros V photograph made on April 18, 1963 (8). This photograph shows wave clouds to the lee of the Appalachians. The wave pattern extends over 100 miles downwind from the first organized wave, which is over the area of the highest peaks, and wave clouds extend for over 200 miles in a NE-SW direction. The wave clouds are parallel to the direction of the general orientation of the Appalachian Mountains. The wavelength in the most regular part of the cloud pattern was about 13 statute miles as measured in the satellite picture. On this day lenticular clouds were observed by ground observers at several weather stations over the eastern part of Virginia. Pilots reported the cloud tops to be mostly below 12 000 feet and clear above. No waves were reported by pilots which could have been due to the long wavelength and the altitude they were flying.

Wave flights are now being made from a number of sites to the lee of the Appalachian Mountains. Over the state of Vermont wave flights have been made as high as 20 000 feet, over western Maryland up to about 17 000 feet, and over western North Carolina to about 20 000 feet.

Figure 6 shows a wave pattern extending from the State of Maine southwest to North Carolina, a distance of about 900 miles. A northwesterly flow of air extended over the entire horizontal extent of these waves and vertically to 500 mb. The photographs to the right of the nephanalysis were made as Tiros VII passed over on November 17, 1964 at 1440 GMT. State boundaries have been superimposed on the photographs to give more exact locations of the wave clouds. Up to now most pilots with some exceptions have been using wave conditions mostly for altitude accomplishments. From this long extensive area of wave clouds it can be seen that there are great possibilities of long distance flights along the Appalachians. Some short flights have been made along these mountains and longer ones are planned.

Wave flight used for distance is not new. On March 19, 1952 J. Kuettner made a flight of 375 miles from Bishop, California to Williams, Arizona in 3 hours and 57 minutes. Just recently S. H. Georgeson of New Zealand, bettered the out-and-back world record with a flight of 460 miles from Omarama, near the Southern Alps. In New Zealand they have speculated that one day a sailplane pilot will break the world distance record flying there in a wave with the possibilities of a 700 mile flight. With the aid of Tiros photographs of waves, cross-country flight in waves can be better accomplished. Cross-country flight using thermals is limited by the hours of thermal heating but when cross-country flight is made in a wave one can start earlier and fly later.

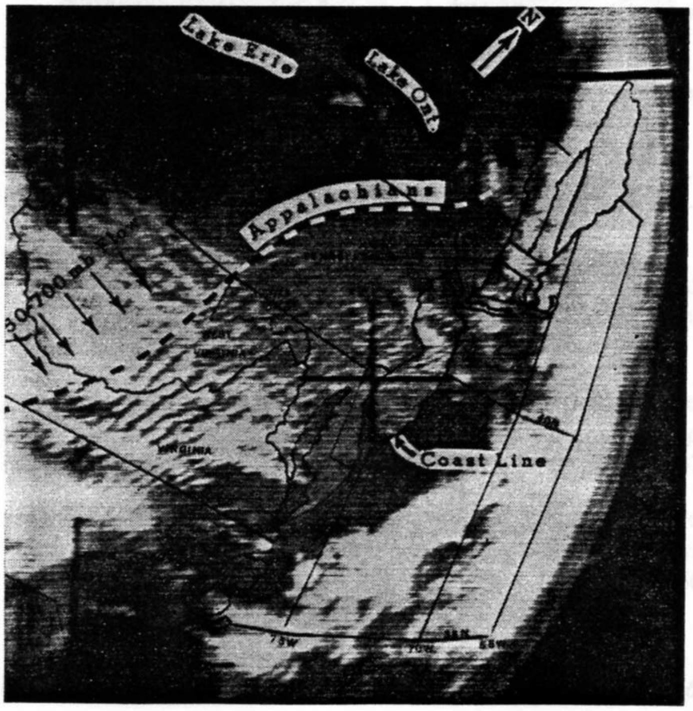
Generally from these photographs one can observe the extent of wave clouds both along the mountains and downwind. In other words the satellite photographs give us more knowledge of the horizontal extent of the waves (depending upon the available moisture) while conventional meteorological observations such as the radiosonde help us in determining the vertical structure of the wave.

Fig. 4. Wave Cloud Pattern over the State of Nevada in the western part of the U.S. as seen by Tiros VII at 1743 GMT on June 6, 1964. Sailplane made flight from Reno, Nevada. (Location indicated by dot on nephanalysis and on Tiros picture.)

4. Determination of wavelength

As already mentioned we can determine the wavelength of the waves. Fritz (9) has used satellite pictures of moun-

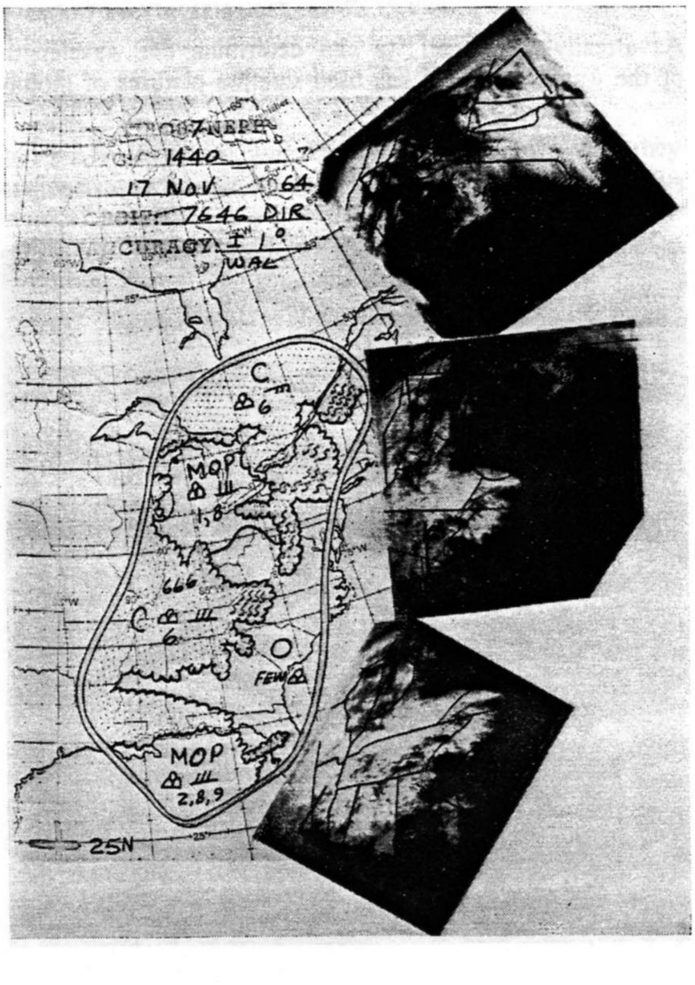
Fig. 5 Wave Cloud Pattern to the lee of the Appalachians, as photographed by Tiros V at 1800 GMT on April 18, 1963



tain waves to estimate the average wind speed in the troposphere as shown on figure 7. Corby (10) has already related the wavelength of lee waves to average wind speeds in the troposphere by using radiosonde data. As we shall show, application of Corby's results generally fits the satellite wave measurements. Satellite pictures of mountain waves were examined by Fritz for possible relationship between the wavelength and average wind speed in the troposphere. It has been estimated that the average wavelength can be determined from satellite data to within about one mile. On figure 7 the wavelengths were plotted against the average wind speed in the troposphere which was taken to be between 850 mb. and 200 mb. On Corby's (1957) graph as shown on figure 7 the unlabelled dots are the results found by Corby, and the straight line is the one he drew to fit his data. The other points labeled with letters, are the results obtained from measurements of satellite photographs of waves made by Fritz. With one exception the results fit Corby's data quite well. Fritz (9) has suggested that this exception was due to less than the usual stability. However, note that the points from the satellite pictures fall to the left of Corby's line. Also note that Corby's points themselves fall to the left when the wavelength is large. It may be that the slope of the line should be somewhat steeper.

The sailplane pilot well knows that if the upper winds in a wave are too strong he will not be able to make much headway in distance along the wave and it will also limit his altitude to some extent. With the wavelength of lee waves varying as indicated by figure 7 with the wind speed with further investigation we should be able to indicate some of the flight characteristics of waves over a given area from the wavelength as shown on a satellite photograph.

Fig. 6. Wave Cloud Pattern to the lee of the Appalachians extending from Maine to North Carolina as photographed by Tiros VII at 1440 GMT on Nov. 17, 1964



5. Present development and availability of satellite photographs

The present quality of the satellite photographs of clouds is very good and will be improved with time. The present use of these pictures as indicators of waves for soaring is restricted somewhat by the delay in the information reaching the forecaster.

After the photographs are received at the readout station they are made into composite sketches (called nephanalyses) of the cloud patterns of several photographs and transmitted on the national weather facsimile network. There has been a delay of about 6 hours in the data reaching the forecaster. It is planned that this will be cut down to about 1½ to 2 hours within a year. One interesting exception occurred when the Satellite Center of the Weather Bureau relayed the latitudes and longitudes of two adjacent wave areas by phone. This information was received within 1 hour after the satellite had passed over. Even receiving the wave observations in a general way such as this is useful to the forecaster.

Timeliness of receipt of the satellite data by the forecaster is important. The usefulness of large scale cloud information diminishes relatively slowly with time, on the other hand data on small-scale systems (such as wave patterns) must reach the forecaster quickly in order to be of maximum use because of the shorter lifetimes of these small-scale structures.

6. Future prospects for satellite wave data

From the point of view of timeliness, a new «Automatic Picture Transmission» system (APT) has been sucessfully tested on Nimbus I and on Tiros VIII. The APT photographs will be reproduced by facsimile recorders rather than by photographing a kinescope presentation, as in the conventional Tiros system. Pictures transmitted on the APT system will be reproduced almost immediately as they are photographed.

When this photo system becomes operational in about a year it will provide cloud-cover pictures at relatively low-cost to ground stations anywhere in the world, whenever the satellite is within radio range. Cost of a typical ground station equipped for the (APT) system, which consists simply of a receiving antenna and amplifier and an FM receiver and the facsimile recording equipment, is about $ 30 000. The National Weather Satellite Center of the Weather Bureau advises that equipment similar to this can be made for as little as $ 10 000 using less expensive components.

The (APT) system will enable the forecaster to acquire directly from the satellite, photographs covering an area of some 1000 miles on a side in the vicinity of the forecasters station. The photographs suitable for use in making detailed, short-period forecasts (such as wave forecasts) will reach the forecaster within five minutes of the time they are taken. This wave data could be made available for immediate relay to wave soaring sites for flight planning or relayed to the soaring pilot while in flight. These (APT) photographs will be available in addition to the current nephanalyses covering broad geographic areas but reaching the forecaster somewhat later.

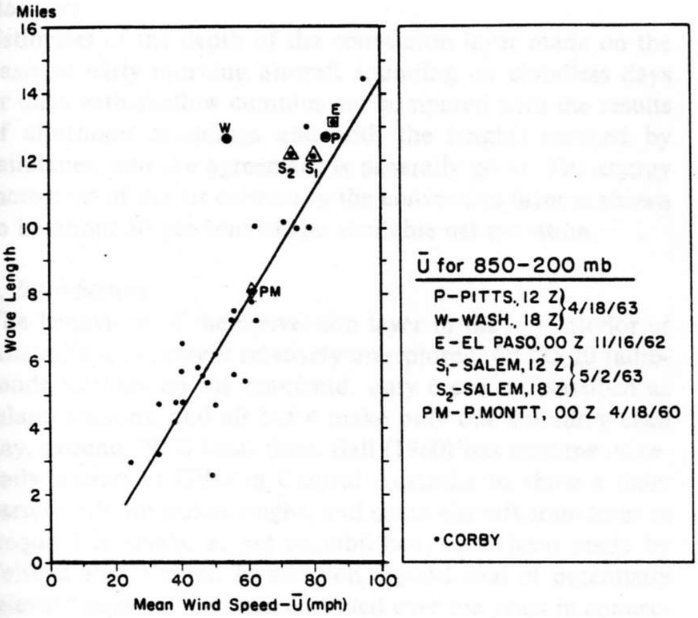


Fig. 7. Relation between wavelength of mountain lee waves and the mean wind speed averaged through the troposphere. The plain dots represent Corby's (1957) data; the other symbols represent results from satellite pictures as pointed out by Fritz

7. Conclusion

As we learn more about lee waves and with the improvement and availability of Tiros photographs we can expect more accurate wave forecasts. Lee waves are better organized and develop more frequently in some areas than in others. As a result of satellite photographs new soaring sites may be indicated plus more information on the frequency of wave occurance.

These photographs can give useful information to aviation in general. Knowledge of the development of mountain waves is significant for purposes of general aviation in several ways. It has long been known that atmospheric turbulence is associated with mountain waves. To the lee of the Appalachian mountains in the eastern United States frequent moderate to severe, low level, turbulence is common when waves are observed. This can be a great hazard to aircraft that have to operate at low levels over mountainous terrain. Also important is the fact that sometimes high level, clear air, turbulence is associated with mountain waves. This has been of some concern to pilots of jet aircraft. The Weather Bureau is currently conducting research on turbulence associated with mountain waves, the jet stream, high level troughs, etc. Records made by soaring pilots of their wave flights can add a significant amount of knowledge to this research.

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