AIAA'87

AIAA-87-0183

Identifying High Altitude Mountain Wave Turbulence and Strong Chinook Wind Events With Satellite Imagery

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AIAA 25th Aerospace Sciences Meeting

January 12-15, 1987/Reno, Nevada

IDENTIFYING HIGH ALTITUDE MOUNTAIN WAVE TURBULENCE AND STRONG CHINOOK WIND EVENTS WITH SATELLITE IMAGERY

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Abstract

A satellite-observed high cloud pattern is described which occurs frequently during incidents of high altitude mountain wave turbulence and strong chinook wind events over the western U.S. Cirrus clouds which approach the steep lee slopes of mountains become thicker and colder downstream from the mountains, with a sharply defined, nearly stationary clearing zone just east of the ridge line. The most significant turbulence occurs under the upstream (western) portion of the coldest cirrus determined from infrared imagery.

Introduction

The occurrence of mountain wave turbulence is quite common at lower levels of the atmosphere (below 20,000 ft), especially during the colder months of the year. At the cruising altitudes of large jets, mountain-induced turbulence is less frequent, although it accounts for about one half of all severe turbulence incidents.[1] When significant turbulence does occur at cruising altitudes, it can be unexpected, sometimes resulting in loss of aircraft control, personal injuries, or even structural damage.[2]

The familiar washboard pattern of low level mountain wave clouds which appears in satellite images has long been associated with turbulence.[3,4] A satellite signature for the presence of high altitude mountain wave turbulence is apparently more subtle and has not been adequately described to date.

One common indication of the effect of mountains on the airflow at high altitudes is orographic cirrus, also referred to as lee-of-the-mountain cirrus.[4,5,6,7] The cirrus plumes form near the crests of mountain ridges and sometimes extends several hundred kilometers downstream. There are usually middle clouds present also, though they are not always visible in satellite images. When viewed in time lapse image sequences, the upstream edge of the cirrus appears to be anchored to the mountains. The cloud top temperatures are very cold (usually -40°C or below), indicating the presence of high, thick cirrus layers. When aircraft fly through this cloud formation, however, the air flow is often smooth. Therefore, some other characteristics must be present to confirm the presence of turbulence.

The purpose of this paper is to summarize satellite image features which were often present during significant high level mountain wave turbulence encounters over the western United States during the period from December to March, 1985-86. Satellite imagery was obtained from the GOES (Geostationary Operational Environmental Satellite) in the infrared (11.5 μm), visible (0.5 μm) and water vapor (6.7 μm) spectral bands. Aircraft pilot reports of turbulence intensity were obtained via relay through the Federal Aviation Administration (FAA) and the National Weather Service (NWS) communications lines.

Description of Satellite Signatures

Infrared

During the period of this study, a significant number of high altitude mountain wave turbulence events over the Rocky Mountains occurred simultaneously with a cloud feature similar to that shown in Figure 1 on 24 February 1986. Cirrus approaching the eastern slopes of the Rockies from the west clears abruptly just east of the ridges in Montana, forming a "trench" which extends southward almost to Idaho. East of the clear trench, very cold, thick orographic cirrus is present, similar to that described in the introduction. Based on cases observed so far, the clear zone is stationary and usually persists for at least two hours.

During the afternoon of 24 February, moderate to severe turbulence was reported, and was accompanied by mountain wave activity. It occurred within 50 nm to the west and southwest of Great Falls, Montana by a DC-8 and Boeing 757 aircraft at altitudes from 35,000 to 43,000 ft.

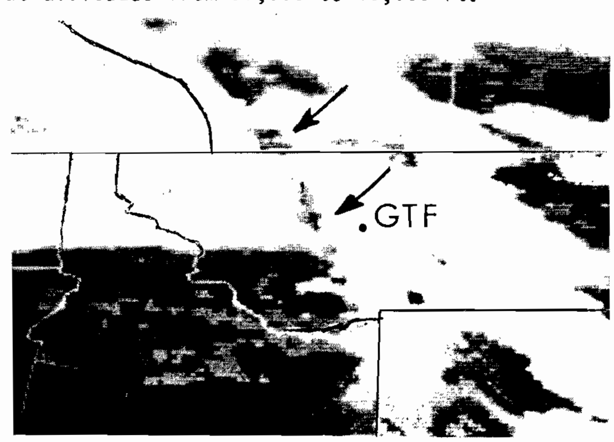

Figure 1. Infrared satellite image for 1900 GMT, 24 February 1986.

This leeside clear trench was probably first reported on by Reid[8] in 1975 for the region of the southern Alps of New Zealand from satellite images obtained from the NOAA-2 polar orbiter. The lee clearing in the cirrus was referred to as the "Foehn gap" since it was associated with warm downslope winds similar to the Foehn winds in central Europe. It was noted that severe low level (below 3km) turbulence occurred in the lee of the mountains. Cloud features similar to these were observed along the east slopes of the Canadian Rockies in Alberta by Lester[9]. The cirrus plumes were considered a high level extension of the "chinook arch," a narrow middle level cloud band associated with long lee waves which sometimes had smaller scale waves embedded.

Based on the cases observed in this study, the main distinction between a turbulent orographic cirrus plume and a non-turbulent one is that for the former, the upstream (western) edge of the coldest cirrus is displaced a considerable distance (30 km) east of the mountain ridges. In the latter case, the cloud edge nearly coincides with the ridge line. Figure 2 schematically shows this relationship.

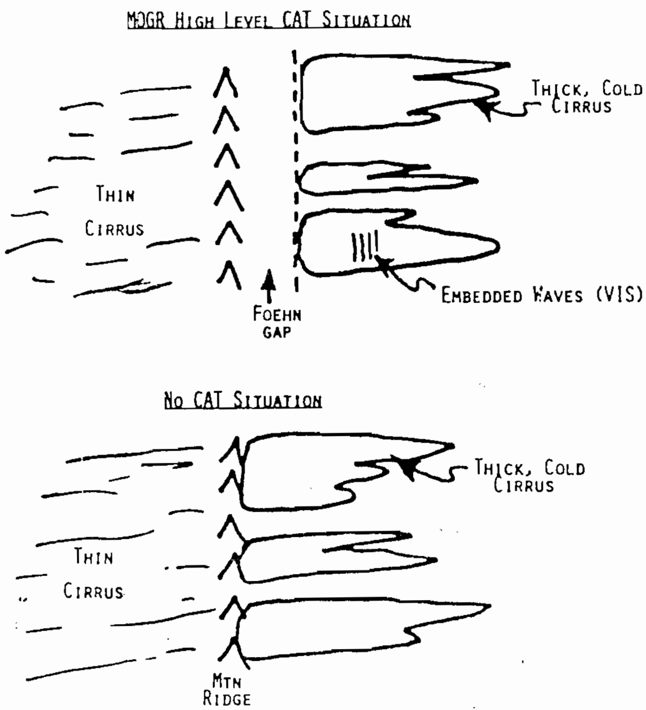

Figure 2. Difference in cirrus cloud patterns for mountain waves with moderate or greater (MOGR) turbulence (top) versus no significant turbulence (bottom).

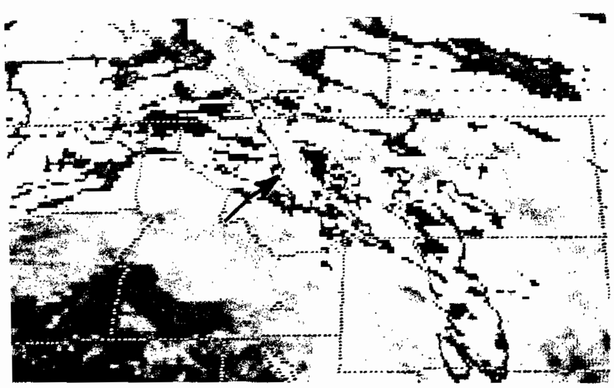

Figure 3. Infrared image enhanced with MB curve for 1801 GMT, 24 February 1986.

Figure 3 also shows the 24 February case, but in this example with an enhanced infrared image. The enhancement is designed to highlight the colder cloud top temperatures, such as those associated with thunderstorms, which it does. It can be seen, however, that the enhancement makes it more difficult to detect the clear zone in the cirrus because of the alternating bands of differing gray shades, combined with darker regions corresponding to the warm ground. Unenhanced imagery is therefore the best type to use, preferably displayed in time lapse motion (looping) to determine if the clear zone and the cold cirrus plume are nearly stationary.

The clear zone in the cirrus may not always be completely clear, but it is normally much thinner than the surrounding cirrus. The thinner cirrus is easily spotted in infrared satellite imagery because larger radiation values from lower levels easily penetrates the cirrus layer and is depicted in the infrared image as relatively warm (dark). Assuming that the clear or thin band in the cirrus is due to strong sinking motion associated with mountain waves, the variability in the appearance of this feature could be related to the (1) intensity or amplitude of the mountain wave and (2) the thickness of the cirrus approaching from the west. Figure 4 is an example for 4 March 1986 in which the leeside clear trench is interrupted by a continuous, thick cirrus plume extending across southern Montana. The thickness of cirrus is difficult to determine in radiosonde data because dew points are not reported at temperatures colder than -40°C.

When the clear zone dissipates and the cold cirrus plume drifts away from the mountains, the worst turbulence is presumed to end, although there have been an insufficient number of reports to confirm this.

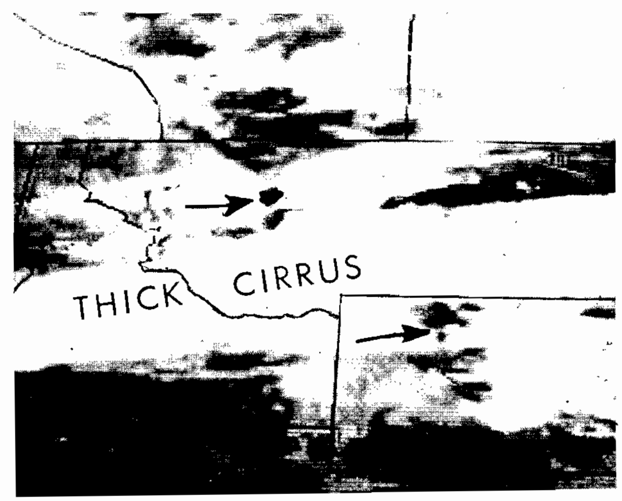

Figure 4. Infrared image for 1900 GMT on 4 March 1986.

Water Vapor Imagery

Water vapor images generated from both the GOES and the European Meteosat display the net radiation in the 6.7 μm portion of the spectrum, a wavelength which is strongly absorbed by water vapor. The response curve for this imagery (e.g., Figure 5) shows a peak in the middle and upper troposphere, principally from about 700 mb to 250 mb. Within this pressure range, the observed image brightness is a measure of the layer thickness, concentration (liquid water content) and temperature of water vapor.[10] Generally, white image areas indicate water vapor at high levels and cold temperatures, while dark areas represent an absence of mid- and high-level moisture. Intermediate gray shades are more ambiguous and relate to varying combinations of moisture and temperature. In areas where cirrus clouds are present, the image greatly resembles the window channel infrared.

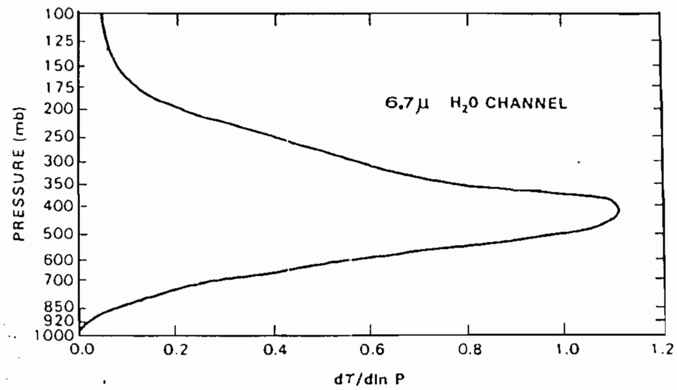

Figure 5. Response curve for 6.7 µm water vapor channel imagery on GOES-VAS instrument.

The clear zone in the cirrus for the case of 24 February appears very pronounced in the water vapor image (Figure 6). A dark band is evident in the same location as the clear zone in the IR image. This indicates that water vapor at high levels has been substantially diminished after passing over the ridges. Any significant moisture must be present at lower levels where the temperature is relatively warm, thus the area appears very dark on the water vapor image. There are instances when dark zones appear in water vapor images just to the lee of the mountain ridges when no cirrus clouds are present. It is not known whether turbulence occurs in these instances or not, as more of these cases need to be studied.

Figure 6. Water vapor image at 1730 GMT, 24 February 1986.

Visible Imagery

The visible image for the 24 February case (Figure 7) reveals the presence of embedded waves in the high clouds just east of Great Falls (GTF), although the waves are not in the vicinity of the reported turbulence. The embedded wave formations suggest the possibility that small scale wave cloud motion may be superimposed on a very long gravity wave as proposed by Lester.[9]

The minimum of cloudiness is evident to the east of the two large mountain ranges in western Montana and shows that the clearing extends down to near the surface.

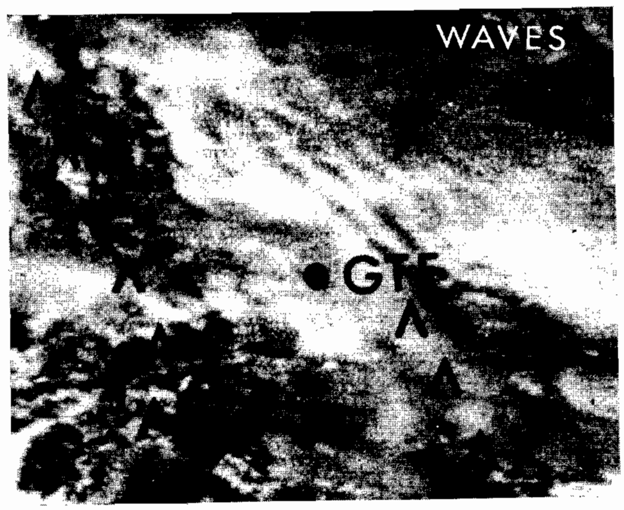

Figure 7. Visible image at 2131 GMT, 24 February 1986. Mountain ridges indicated by (/\). GTF is Great Falls, MT.

Description of Cases

During the period of this study, there were ten days when the turbulence signature described above appeared in a well-defined manner. These are summarized in Table 1. All of the cases occurred over the western United States, mostly at the abrupt eastern slopes of the Rockies in western Montana, Wyoming, Colorado, and northern New Mexico. In nine of the ten cases (90%), moderate or greater intensity turbulence was reported, at altitudes above 26,000 ft MSL. Six of the cases had at least one report of severe turbulence.

Additionally, on all of these days there were very strong westerly chinook winds at the surface. Maximum gusts exceeded 50mph on each day and reached 100 mph on 14 February and 24 February (source: NOAA Storm Data and National Weather Summaries issued by the National Severe Storms Forecast Center in Kansas City). In these strong lee slope windstorms, the occurrence of severe low level turbulence has been well established.[11]

Although the percentage frequency of high level mountain wave turbulence with the cirrus-free trench pattern is very high, there are mountain wave events with which no distinctive features were observed in satellite images. The absence of the cloud features is, of course, related to the lack of high level moisture in the westerly flow aloft.

TABLE 1

SUMMARY OF CASES

DATE	LOCATION	TURBULENCE INTENSITY	MAXIMUM SURFACE WIND (MPH)
Dec 3, 1985	Colorado	Mdt - Sev *	45
Jan 2-3, 1986	Colo.-New Mexico	Mdt - Sev	82
Jan 10	NW Montana	None reported	58
Jan 19	NW Mont., Wyo.	Mdt	50 - 60
Feb 13	Colo., NM	Mdt - Sev	69
Feb 14	Colo., NM S Cal.	Mdt - Sev	50 - 100
Feb 16	Colo., Wyo.	Mdt - Sev	60
Feb 24	Montana	Mdt - Sev	100
Mar 4	Mont., Colo.	Mdt - Sev	40 - 60
Mar 7	Montana	Mdt	50

* Mdt = Moderate turbulence
Sev = Severe turbulence

Atmospheric Conditions

Upper Level Synoptic Pattern

Most of the high wind and turbulence episodes occurred just east of an upper level ridge of high pressure. Pressure heights (analogous to isobars on a constant height pressure analysis) were often rising, in response to an approaching short wave trough/ridge couplet in the westerly or northwesterly flow. The maximum jet stream winds were normally to the north of the affected area. This resulted in anticyclonic shear and curvature, which tends to create high stability. The 200 mb upper air analysis from the National Meteorological Center (NMC) for 1200 GMT 24 February (Figure 8) is an example of these conditions.

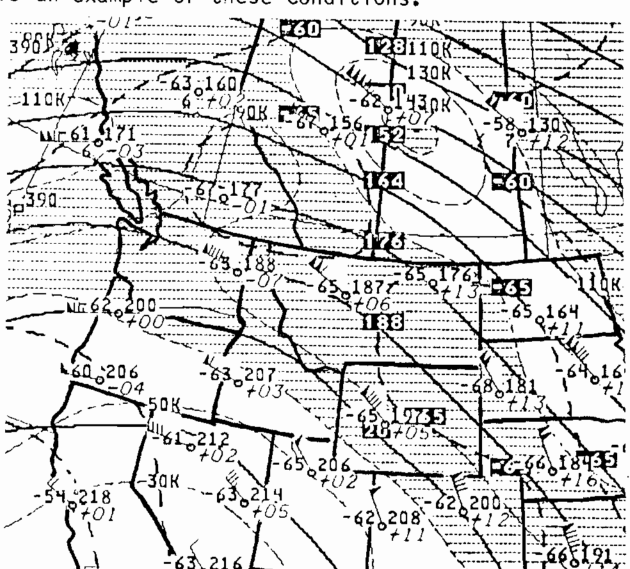

Figure 8. Upper air analysis for 200 mb at 1200 GMT, 24 February 1986.

Vertical Profiles of Wind and Temperature

Radiosonde data were examined for each of the ten cases at adjacent upper air stations. The times of the radiosondes were mostly at 1200 GMT (0600 CST), prior to the turbulence reports.

Upper winds were strong out of the west or northwest with a component nearly perpendicular to the mountains. Winds increased with height to maximum values of 75 kt or more in the upper troposphere. A few soundings had layers of significant vertical wind shear (6 kt /1000 ft or more) but many did not.

In all cases, the tropopause was very cold with temperatures of -61°C or less. The average temperature was -65°C, with the average tropopause height close to 40,000 ft MSL (12.1 km). Such conditions were noted as essential for upper level mountain waves and are important criteria for United Airlines forecasters.[1] Furthermore, the strength of the inversion associated with the tropopause was marked. At lower levels, a stable layer was usually present near the mountain tops (near 700 mb), with less stability above extending to the tropopause. The radiosonde for Great Falls, MT at 1200 GMT, 24 February is shown in Figure 9 as a good example of upper air conditions normally present.

The height of the upper level wind maximum obtained from the radiosondes was below the tropopause in nearly all cases. The average height difference was about 5,000 ft (1.6 km). Numerical simulations of mountain wave conditions[12,13] have shown that layers where the winds decrease with height tend to produce mountain waves which steepen with time, become unstable and break, resulting in strongly turbulent conditions.

Surface Pressure

The surface pressure patterns observed were quite similar to other cases of strong chinook wind conditions.[9] On 24 February, for example, high pressure was centered over the Great Basin of Utah and Nevada with a trough of low pressure extending along the lee side of the mountains from Alberta to western Nebraska (Figure 10). This created a strong pressure gradient across the mountains, especially in Montana. The geostrophic winds determined from the gradient of altimeter settings[14] are shown in Figure 11. Winds of 30 to 50 kt are indicated along the east slopes of the mountains. Maximum wind gusts of 100 mph were reported in northwest Montana during the afternoon.

Location of Turbulence Relative to Cloud Pattern

The sporadic nature of routine aircraft turbulence reports makes it difficult in most cases to pinpoint the location of the turbulence with respect to observed cloud features. On 24 February, however, several reports of moderate to severe turbulence within 50 nm southwest of Great Falls suggest that the turbulence was beneath (or within) the westernmost portion of the cold, enhanced cirrus plume (in other words, just east of the clear zone).

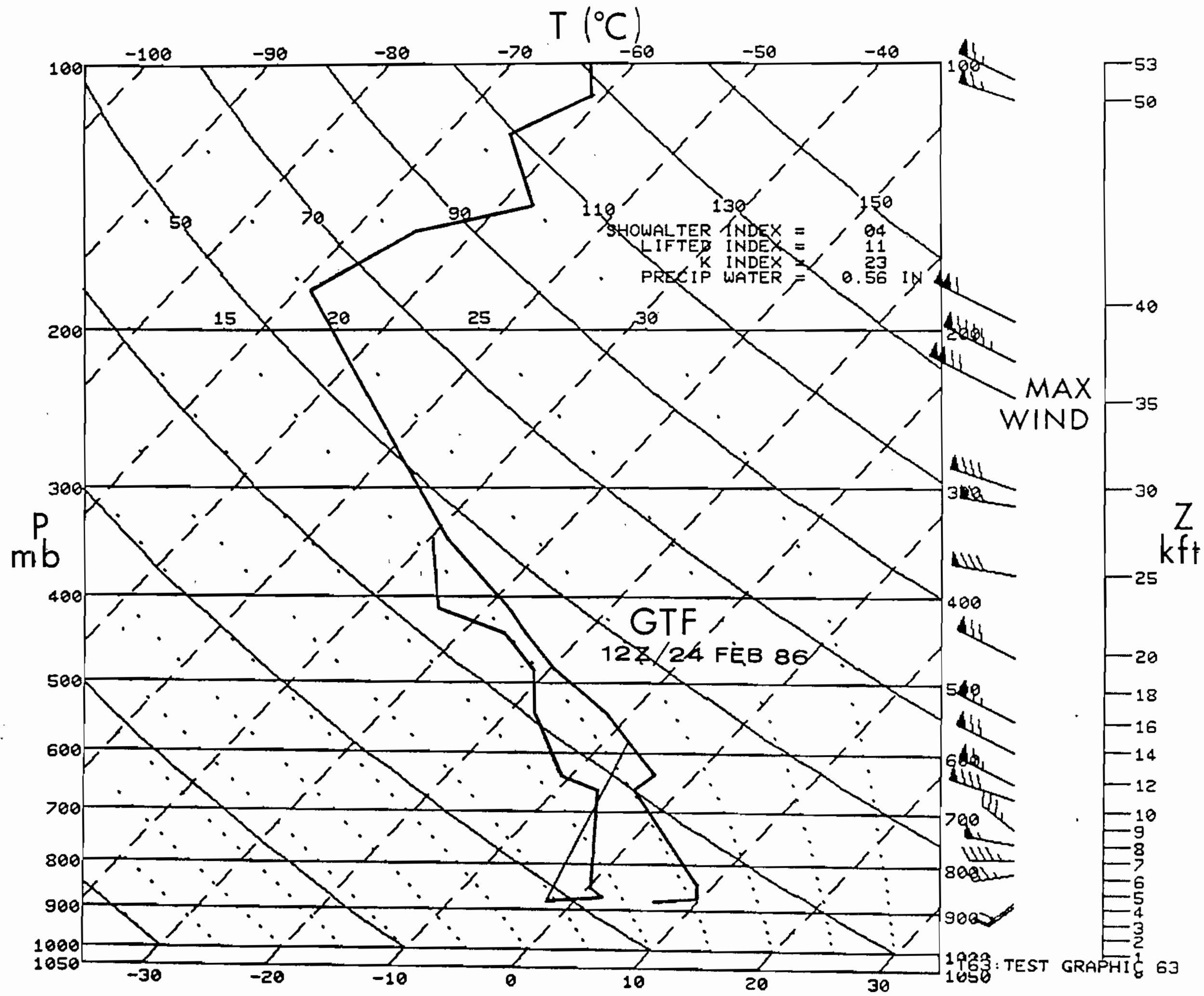

Figure 9. Skew-T plot of rawinsonde data for Great Falls, Montana at 1200 GMT, 24 February 1986 as displayed on NWS AFOS (Automation of Field Operations and Services) computer system.

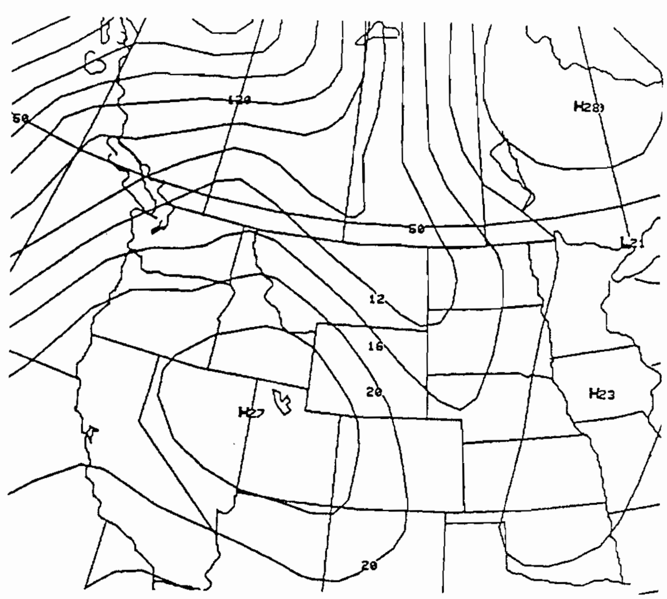

Figure 10. Surface pressure analysis at 1200 GMT on 24 February 1986.

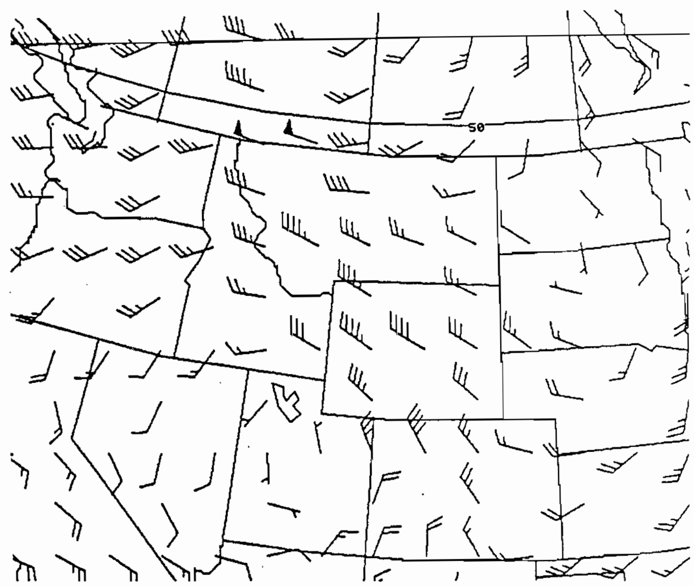

Figure 11. Surface geostrophic wind chart for 1800 GMT on 24 February 1986.

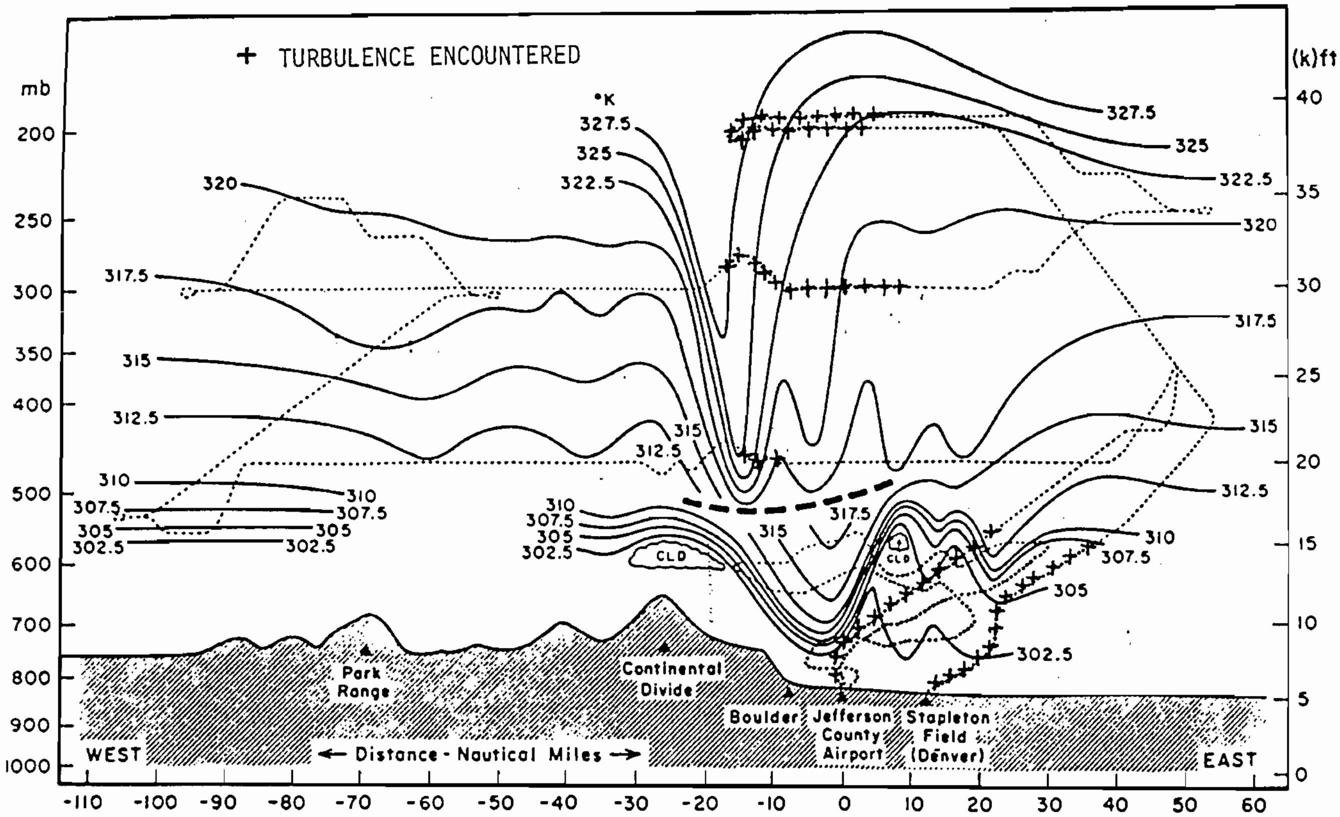

Figure 12. Cross section derived form aircraft and radiosonde data on 11 January 1972. Location of significant turbulence is shown by pluses(+). Potential temperatures are in °K. (After Lilly, 1978)

More detailed turbulence data were analyzed in earlier case studies of chinook wind conditions. Lilly[10] analyzed data from a severe lee slope windstorm in central Colorado on 11 January 1972. Severe to extreme turbulence was encountered by a research aircraft from near the surface up to 40,000 ft. A potential temperature cross section for this case is shown in Figure 12 with significant turbulence marked by plus symbols. Assuming the air flows along the potential temperature surfaces (a good assumption for unsaturated air and even for saturated air at high altitudes), most of the turbulence a high levels occurred in the steep, vertically ascending portion of a pronounced mountain wave. Although satellite images were not available for this date, the location of turbulence would probably correspond to the upstream portion of any leeside orographic cloudiness.

Another case involving a weaker chinook wind situation in southern Alberta[15] showed light to moderate turbulence in the same location with respect to a chinook arch cloud. The mountain wave diminished in amplitude with height and shifted closer to the mountains.

Forecasting Applications

The presence of the mountain wave signature in satellite imagery should be quite valuable to aviation forecasters and especially flight briefers for the detection and short range forecasting of high level mountain wave turbulence. This is because of the scarcity of aircraft reports during certain times of the day and over some less heavily traveled air routes such as the northern Rockies. Sometimes the cloud pattern will be observed first at an upstream mountain range, such as the Wind River range in northwest Wyoming, thus providing some lead time for downstream locations in Colorado. The dissipation of the signature should signal an end to the severe turbulence conditions.

Although the events observed during this study were over the western U. S. and southern Canada, other major mountain ranges such as the Andes and the Alps of central Europe should provide a favorable environment for the development of such waves and their resultant cloud formations.

The mountain wave cloud pattern appears to have less value in the nowcasting of strong chinook winds, mainly because of the relatively dense surface reporting network and the improved knowledge of conditions normally preceding these high wind events[16]. A recent study[17] has shown, however, that low level inversions present prior to strong leeside windstorms may require some time to erode before the strong winds can reach the surface. Further study is required to determine if the high level mountain wave signature can provide some forewarning of these events. If it does, it is likely that the lead time would be rather short (1 hr or less).

Acknowledgements

The author thanks Ralph Anderson and Andy Timchalk of NESDIS for their review of the paper, Tina Cashman for assisting with the final typing and John Shadid for the layout of the final copy.

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