Mountain Lee Waves of the Southern Rockies

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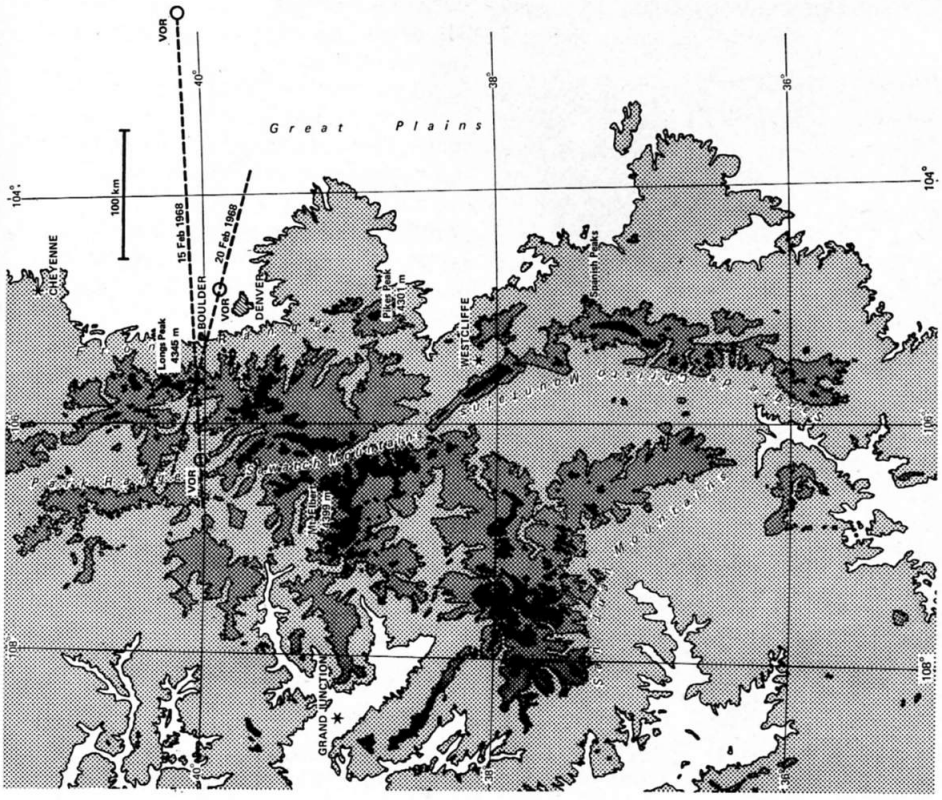
The Rockies form a chain of mountains, almost 4,000 km long, running between the southern part of the USA and the northern coast line of Alaska. Although they appear to form a continuous range on a global map, they are divided into four parts, the southernmost being in Colorado and New Mexico and called the «Southern Rocky Mountains». As seen in figure 1, they consist of a number of mountain ranges, most of them running roughly in a north-south direction and having crests between 3,000 and 4,000 m, while the plains to the east are only 1,500 m high. The main mountain range west of Boulder is called the «Front Range» with peaks over 4,000 m. The west-east profile of the Front Range does not vary much if the plane of the cross section is moved north or south. This part of the Front Range was therefore considered suitable for testing 2 dimensional theories of airflow over mountains.

On the eastern side of the Rockies one often finds Föhn type winds which are locally known as «The Chinook». They are connected with mountain waves and occasionally reach hurricane force at the surface with gusts up to 200 km/h, uprooting trees, lifting roofs of houses, blowing cars off roads or trains off their tracks. Mountain waves have been used in Colorado by sailplane pilots since the late thirties, heights to 12.5 km have been reached near Pikes Peak (fig. 1). An example of severe mountain lee waves of the Southern Rockies affecting powered aircraft is the case of the USAF bomber which was used for atmospheric research and, flying in the lee of the Spanish Peaks (see fig. 1), lost part of its rudder and vertical stabilizer in severe clear air turbulence but landed safely. It seems likely that many fatal accidents with light airplanes occurring in the Southern Rockies are due to the inability of many pilots to cope with mountain lee wave conditions.

Fig. 1. The Southern Rocky Mountains. Black indicates ground above 3,600 m, dark shading above 2,700 m and light shading above 1,800 m. Dashed lines: flight tracks flown.



Background of the February 1968 Mountain Lee Wave Project

It is, with our present knowledge, nearly impossible to predict when the Chinook is going to be destructively strong. Lilly, a scientist at NCAR, decided to study the whole mountain lee wave phenomenon, hoping that this would help to improve the forecasts. He began with one of NCAR's Beech Queen Air aircraft and used a surface network of wind recorders. The work of his group attracted the attention of many other groups in the USA and Canada, and resulted in the cooperative lee wave project conducted in February 1968.

Participants of the Project

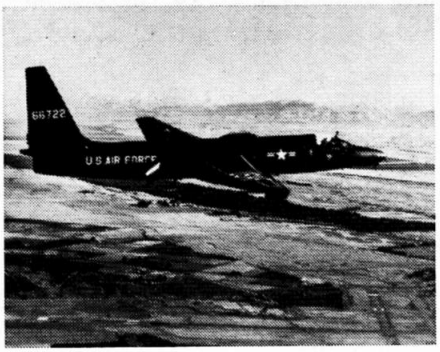
Table I lists the agencies that took part in the project and gives some information on the aircraft and instrumentation carried by them. The sailplane was a Schweizer 2-32. For rough position determination it could use its VOR equipment and DME (Distance Measuring Equipment). Photos of the various aircraft participating in the project are shown in figure 2. The pilot of the Schweizer 2-32 sailplane was Captain Scribner. The most interesting data come from the U-2 flying at altitudes of nearly 20 km.

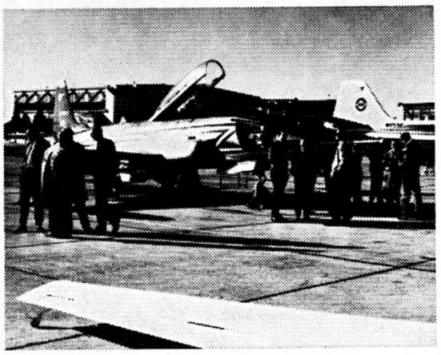
The Observations

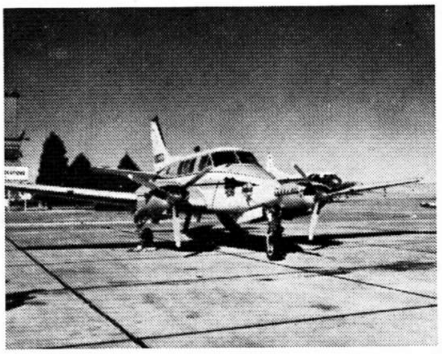
During this project the aircraft flew in a vertical stack along the tracks shown in figure 1, going back and forth over a distance of about 250 km length at varying heights. Each aircraft covered a certain height interval by flying in steps of about 1,000 m. The NCAR Queen Air covered the lower levels, the Canadian T-33 the middle troposphere, the ESSA B-57 the upper troposphere and lower stratosphere, and the U-2 the higher stratosphere. All aircraft flew constant pressure altitude to the extent possible. By measuring temperature and winds, the stream lines could be constructed from the potential temperature and wind field.

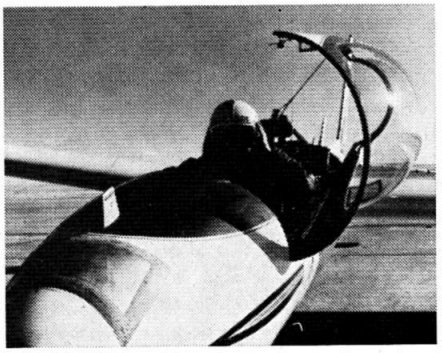
February 1968 was weatherwise not the best month for mountain lee wave studies. There were, however, some interesting days with westerlies from the surface up to 20 km. Although no days with really strong mountain lee waves were encountered, the wave activity in the stratosphere was surprisingly strong and actually increased with height.

Fig. 2. Aircraft participating in Project. (Top to bottom, left: U-2, B-57, Comanche; right: T-33, Queen Air, 2-32.)









A summary of all the flights is given in table II. The situations of 15 and 20 February were selected as the most interesting for discussion here.

15 February 1968

The flights took place between approximately 15.00 and 17.00 local time. Surface winds in Colorado were light and variable. At 500 and 200 mb the airflow was from the west over most of the United States (fig. 3). Over Colorado, the wind strength was of the order of 25 m/sec at 500 mb (5.6 km) and of the order of 35 m/sec at 200 mb (11.7 km).

Like on all other days, the aircraft flew in a vertical plane which was not far from perpendicular to the mountain range. Lines of constant potential temperature were obtained for this plane from aircraft, radiosonde, and surface data, and are shown in figure 4; where the flow may be assumed to be adiabatic these lines may be interpreted as stream lines. The dotted lines represent the trajectories flown. The Queen Air flew between 5 and 7 km ASL and the flight path was affected by up and down drafts. One roll cloud was observed. The lines of constant potential temperature below the lowest flight level of the Queen Air are based on the data at this level, and some surface data. (Near the surface the airflow cannot be expected to be adiabatic, and the lines of constant potential temperature can thus not be interpreted as stream lines.)

The B-57 flew between 10.5 and 13 km at constant levels. The dominant wave length in the B-57 region of the flow pattern shown in figure 4 is obviously considerably longer (35 km) than the dominant wave length below, the latter being approximately 15 km. This is predicted by theory. Shorter wave length components were also present at the B-57 levels, but there appeared to be very little correlation between two successive traverses. These shorter components were therefore smoothed out.

The U-2 obtained data in the region between 16 and 20 km. These data were similarly smoothed. The most dramatic result of these flights is the increase of wave amplitude with height in the stratosphere which at 20 km height almost reaches the maximum wave amplitude at 6 km height. Since severe turbulence was encountered at these levels, the unsmoothed data are of more interest. They are shown in figure 5. The potential temperature line for 420°K appears to be S shaped suggesting a breaking wave. Since the potential temperature at A is greater than the potential temperature at B, the lapse rate would be super adiabatic in this region (cross hatched area in the diagram).

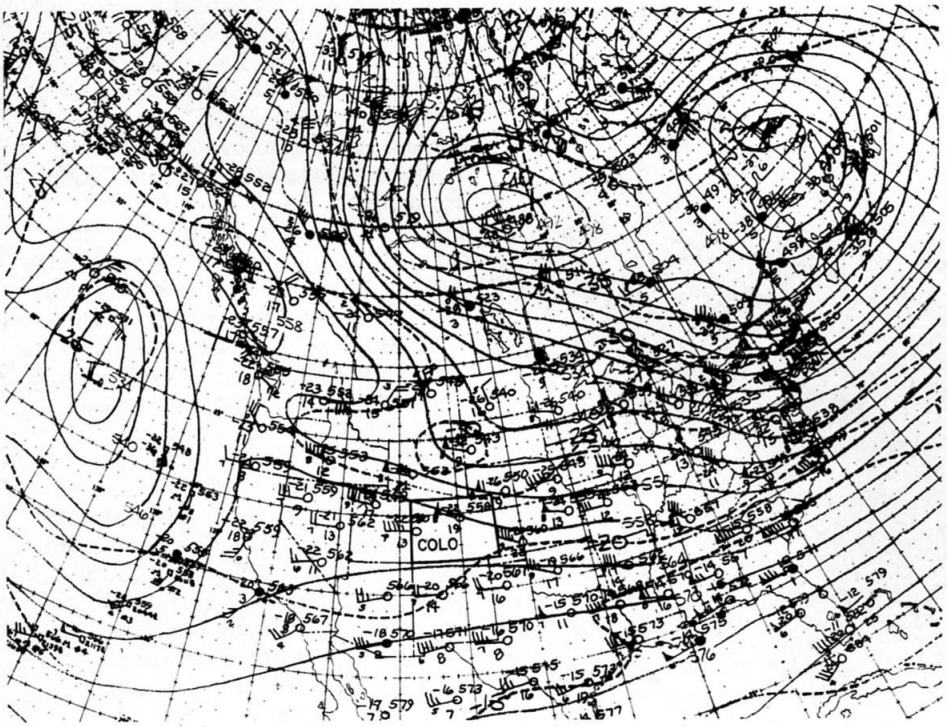


Fig. 3. 00.00 Z. 16 February 1968 (17.00 local time, 15 February), 500 mb chart.

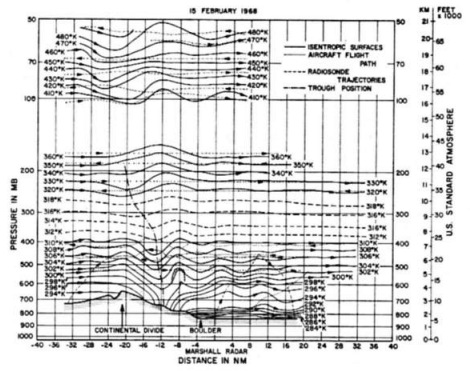


Fig. 4. Potential temperature analysis for 15 February 1968.

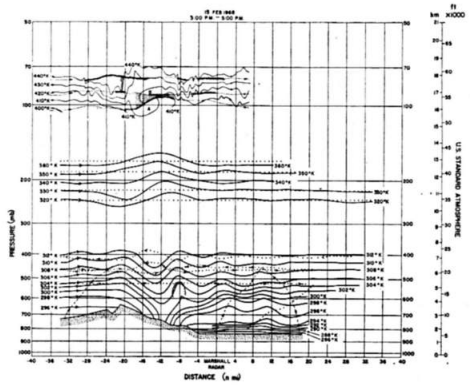


Fig. 5. Same as figure 4 but unsmoothed data of the U-2

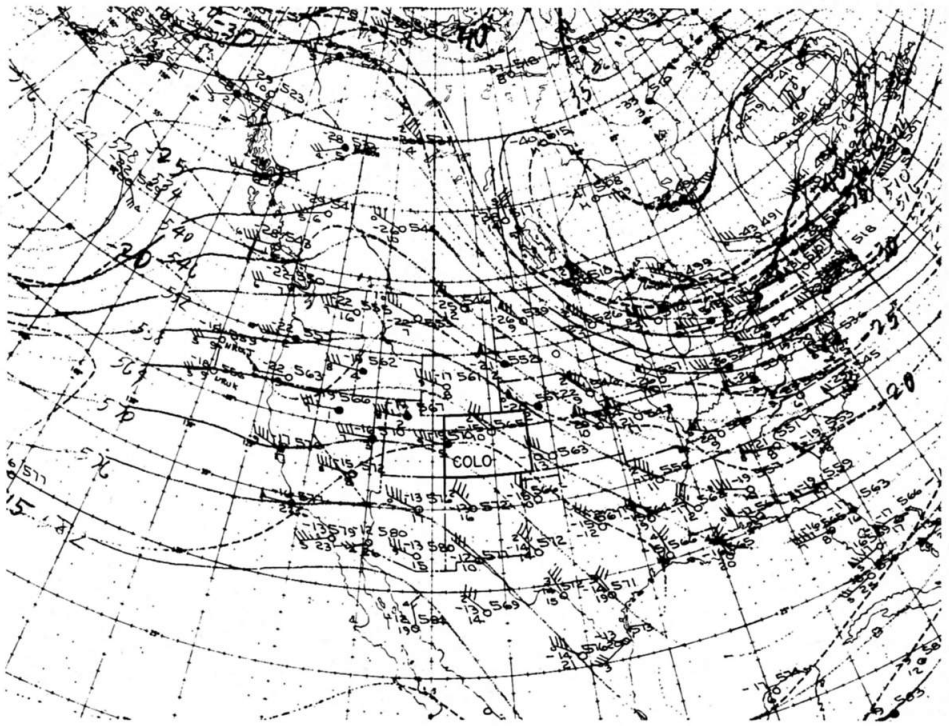


Fig. 7. 12.00 Z (05.00 local time), 20 February 1968, 500 mb chart.

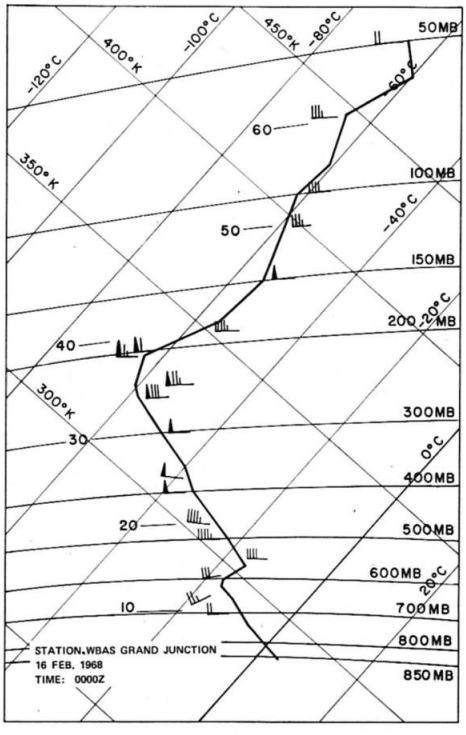


Fig. 6. Wind and temperature sounding from Grand Junction (upwind) at 17.00 local time, 15 February 1968.

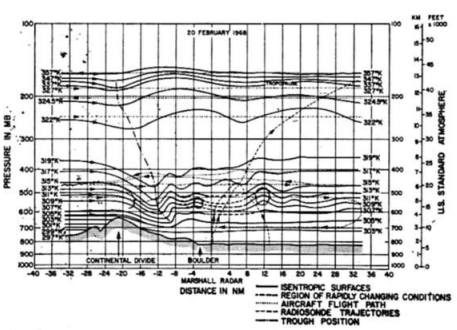


Fig. 8. Potential temperature analysis for 20 February 1968.

The time difference between the passages at A and B is of the order of 10 min and it seems unlikely that a potential temperature field of this nature can be maintained without deteriorating into turbulence.
The zigzags along the U-2 trajectories indicate rapid successions of vertical acceleration of more than ±0.5 g as recorded by an accelerometer. The upwind sounding from Grand Junction (fig. 6) shows maximum wind speeds of around 35 m/sec near the tropopause (10.5 km) and a strong inversion just above 600 mb.

20 February 1968

Flights were made by the Queen Air, T-33, B-57, and the Schweizer 2-32 sailplane. The winds were more from the northwest (fig. 7). The flights took place between 08.30 and 10.30 local time. A stationary front just touched the northeastern corner of Colorado. The surface winds in Colorado were light and variable. Over Colorado a WNW airstream was found with winds of the order of 10 m/sec at mountain level, 20 m/sec at 500 mb (5.5 km), and 40 m/sec at the 200 mb level (12 km).
Figure 8 shows the potential temperature analysis which is based on data from the Queen Air up to 7 km, from the B-57 between 10.5 and 13 km and on surface data. A thick cap cloud obscured the crest of the Front Range. A broad downdraft was present above the Front Range. The 319 °K line dips from a pressure altitude of 7.7 km down to around 5.8 km, a drop of almost 2 km. Notice how the airstream bounces up and goes through several wavelengths before the original level is re-obtained. Approximately four wave lengths of around 13 km each seem to be superimposed on one huge dip.
Two rotor clouds were observed. The data between these rotor clouds were difficult to analyze. It was concluded that the flow pattern was time dependent in this region. In the tropopause region (around 12.5 km; 327 °K) the dominant wavelength was again much longer, approximately 45 km.
The Grand Junction sounding (fig. 9) shows a maximum in wind speed near the tropopause of approximately 50 m/sec. The winds were consistently from the NW through the whole sounding. Noteworthy are the variations found above the tropopause. These are often connected with Clear Air Turbulence. Unfortunately, the U-2 did not fly on this day.
Although the project was somewhat improvised in nature it turned out to be very successful. Those involved were already thinking in terms of a future project in which advantage could be taken from the experience gained. If such a project were realized, one might hope to encounter eventually a case like that illustrated in figure 10, which was photographed from Boulder several years ago.

Continuation in 1970

A continuation of the project described was conducted in 1970. Figure 11 shows how different the waveflow

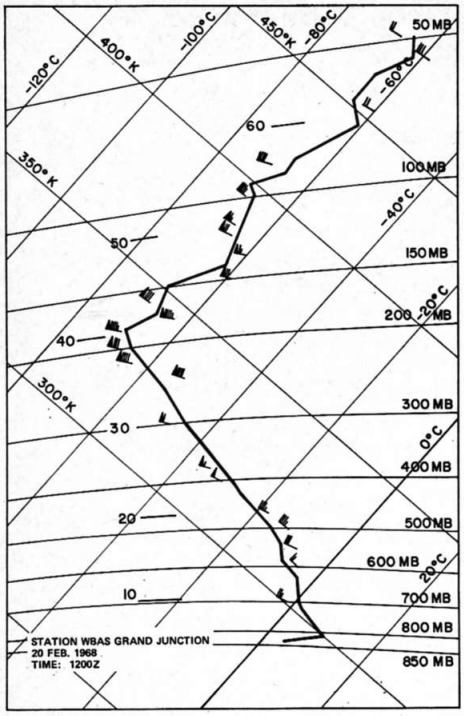


Fig. 9. Wind and temperature sounding from Grand Junction at 12.00 Z (05.00 local time), 20 February 1968.

Fig. 10. Large wave cloud over Boulder.

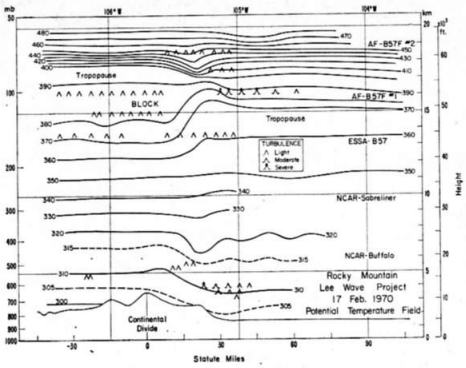


Fig. 11. Potential temperature contours for 17 February 1970.

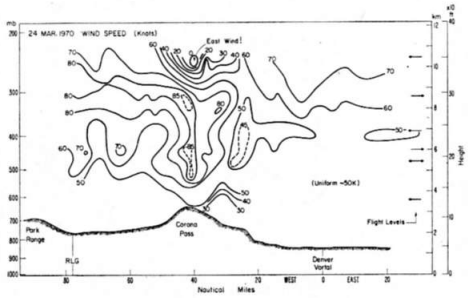


Fig. 12. Wind contours for 24 March 1970.

Table I. Instrumentation

Agency	Aircraft	Missions flown	Altitude and speed	Temperature response	Static pressure	Humidity response	Airspeed	Winds	Acceleration	Gust probes	Airplane orientation (and location)	Recording	Other
Air Force (HICAT Program)	U-2	5	50,000–70,000 ft	fast	×	–	×	inertial platform	three component	two vanes	inertial platform	analog magnetic tape	structural strain instruments
Canadian National Aircraft Establishment	T-33	8	24,000–40,000 ft 400 kt	fast	×	–	×	Doppler	three component	two vanes	rate and attitude gyros (Doppler)	analog magnetic tape	thermal turbulence detector
ESSA Research Flight Facility	B-57	8	25,000–45,000 ft 400 kt	medium (2 sec)	×	–	×	Doppler	–	–	1 attitude gyro (Doppler)	digital magnetic tape	radio altimeter
NCAR	Queen Air	12	10,000–25,000 ft 170 kt	fast (0.02 sec) and medium (2 sec)	×	slow (1–10 sec)	×	Doppler	vertical	two vanes		digital magnetic tape	rate of climb
White Sands Missile Range	Comanche	2	5,000–15,000 ft	medium	×	–	–	–	–	–	–	analog tape	ozone
Explorers Research Corporation	2–32 sailplane	4	5,000–30,000 ft 60 kt	medium	×	–	–	–	three component	–	(radar tracking or VOR/DME)	oscillograph	thermal turbulence detector

Table II. Flight summary, February 1968

Date	Area and track	Aircraft	Upstream winds				Wave activity		Turbulence
			direction (°) 500 mb		speed (kt) tropopause		wavelength	peak-to-peak streamline amplitude	
			°	kt	°	kt			
13	Denver W	QA, T-33	240	27	250	55	uncertain	very weak	none
14	Pueblo WSW	T-33, B-57, U-2	220	10	235	40	15 km	400 m	light
15	Denver W	QA, T-33, B-57, U-2	275	48	260	60	16 km (low levels) 30 km (tropopause)	2,000 m (low) 1,700 m (high)	moderate to severe in stratosphere
16	Denver WNW	QA, T-33, B-57, U-2, sailplane	280	38	280	75	15 km and longer	1,600 m (low) 600 m (trop)	moderate low levels and stratosphere
18	Denver WNW	QA, T-33, B-57 sailplane	310	39	320	45	irregular and 3-dimensional	300 m	moderate all levels
19	Denver W	QA, T-33, U-2	290	55	310	70	irregular and 3-dimensional	2,000 m (low)	moderate to severe low levels and stratosphere
20	Denver WNW	QA, T-33, B-57 sailplane	285	70	290	90	11 km (low levels) 45 km (tropopause)	2,000 m (low) 1,000 m (trop)	light, moderate in rotors
25	Denver WNW	QA, B-57, Comanche sailplane	310	50	290	60	single wave	800 m (low) 400 m (trop)	light

can be under different atmospheric conditions. On the 17 February 1970 the how level waves died out quickly with height, but a very large pressure-jump-like wave with almost 10,000 ft amplitude developed at the 50,000 ft level with complete blocking action upwind. The wave is still noticeable at 60,000 ft. Fig. 12 shows how. On the 24 March 1970 the wind velocity changed from 85 knots West at 30,000 ft to a slight East wind at 35,000 ft. These two cases were presented at the 12th OSTIV Congress by Dr. D. Willy and Dr. E. Zipser, NCAR, Boulder, Colorado.

References

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3 Lilly, Douglas K. and Toutenhoofd, W.: The Colorado lee wave program; in Pao and Goldberg, Clear air turbulence and its detection, p. 232 (Plenum Press New York 1969).