An Investigation of Mountain Waves with Lidar Observations[1]

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ABSTRACT

In March and April of 1969 and 1970, lidar (laser radar) observations of the atmospheric structure were made in the lee of the Sierra Nevada during the occurrence of mountain lee waves. Rawinsonde ascents and, on some occasions, research aircraft flights supported the lidar observations. The objective of the program was to explore the applicability of the lidar technique to atmospheric turbulence detection. The observations demonstrate that a ground-based lidar can delineate significant features of the atmospheric flow pattern by monitoring echoes from concentrations of particulate matter that characterize the airflow structure in the form of either visible or subvisible clouds and dust.

1. Introduction

The development of wave motion in a stably stratified airflow crossing a mountain barrier is well documented and formulated in the literature on the basis of theoretical studies and observational programs (e.g., Corby, 1954; Alaka, 1960; Foldvik and Wurtele, 1967). A mountain barrier of major importance in the generation of such wave motion is the Sierra Nevada; its lee waves were the subject of intensive investigation during the well-known Sierra Wave Project (Holmboe and Klieforth, 1957).

It is in connection with investigations of high-level turbulence and its possible role in the evolution and maintenance of the large-scale atmospheric circulation that studies of the atmospheric structure in the lee of mountains have been resumed in recent years (Kuettner and Lilly, 1968; Wooldridge and Lester, 1969; Lilly, 1972). High-level turbulence is known to be associated with mountain barriers and mountain lee waves (Harrison and Sowa, 1966; Reiter and Foltz, 1967).

The general objective of the observations described in this paper was to evaluate the potential of lidar (optical radar) to monitor the atmospheric structure in the lee of a mountain barrier during the occurrence of lee waves. The particular objective was to establish to what extent lidar observations (from the ground, as in this study, or subsequently from an aircraft) can be used to delineate or interpret the air flow for the detection or anticipation of turbulence. For this purpose, series of lidar observations were made in the southern Sierra Nevada in the lee of Mount Whitney (14,495 ft MSL) during March and April, 1969, and also in the northern Sierra Nevada in the lee of Mt. Rose (10,778 ft MSL) during March and April, 1970. Most observations were made at time periods during which the occurrence of waves was evident from the presence of lenticular clouds and/or rotor clouds. Detailed analyses and discussions of the lidar data are presented by Viezee (1970).

This paper summarizes the lidar/mountain-wave observation program and extends and clarifies the lidar observations of Sierra-wave conditions made initially by Collis *et al.* (1968) at Independence, Calif., during February and March, 1967.

2. Technique of observation and data analysis

The development of lidar has introduced a new remote atmospheric probing technique. A pulsed laser in the visible or near infrared spectrum can remotely detect particulate matter of much smaller size and much lower concentration than can be seen by the human eye or "seen" by a microwave radar. Lidar, therefore, can be used to detect aerosol concentrations in the visually clear air, and can also map the spatial extent and temporal variations of tenuous and small-particle clouds. This new capability has led to the suggestion that lidar be used to detect clear air turbulence. A reasonable approach appears to be the identification of the general air flow pattern from lidar observations of particulate matter, with the subsequent recognition of areas prone to turbulence that are present or may develop in the flow conditions in question (Collis,

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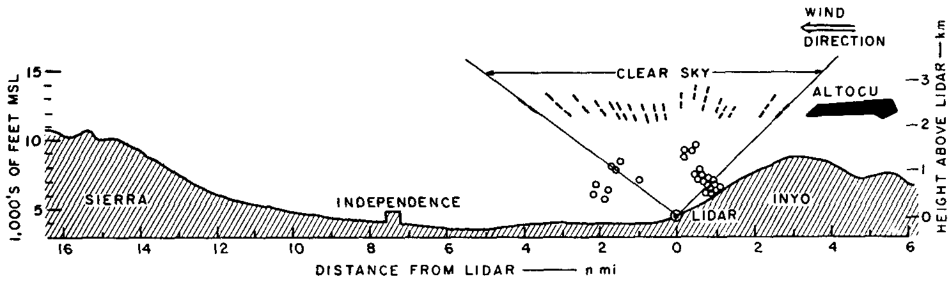
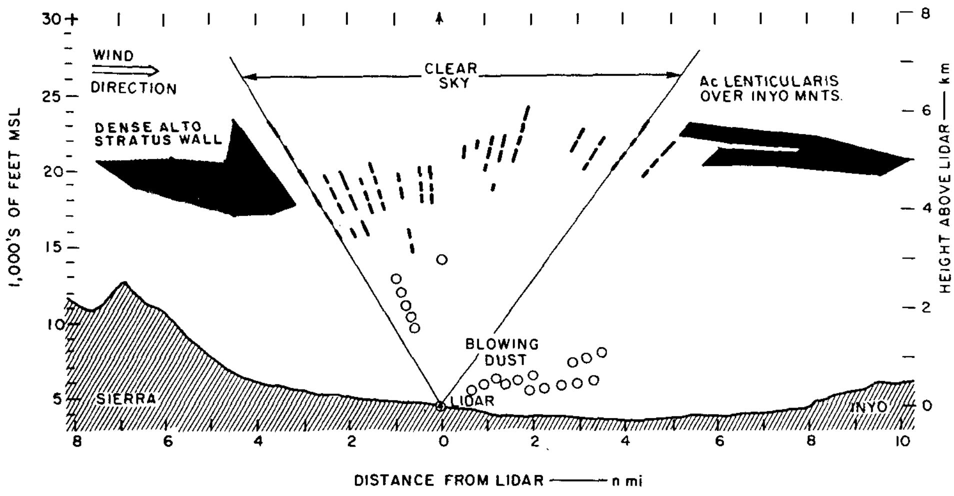


(a) INDEPENDENCE, CALIFORNIA, 19 February 1967, 13:22-13:43 PST



(b) LONE PINE, CALIFORNIA, 20 MARCH 1969, 15:48-16:25 PST

Fig. 1. Vertical cross sections (looking toward north) showing similarity in atmospheric structure observed by lidar during wave conditions over Owens Valley on two separate occasions. Shading, visible clouds; dashed lines, subvisible structure; open circles, visible dust.

1964). This approach was applied to mountain waves. The observations in the southern Sierra Nevada were made with the SRI Mk V lidar, the characteristics of which are listed elsewhere (Viezee and Oblanas, 1969). The Mk VII lidar was used during the experiment in the northern Sierra Nevada in March and April, 1970. Its characteristics are identical to those of the Mk V except that the 6-inch Newtonian reflecting telescope of the transmitter optics is replaced by a 2-inch refracting lens. This modification was made for the purpose of eliminating any interference of the field stop with the outgoing pulse shape.

Observations were made by firing the lidar at selected intervals in elevation angle while scanning from horizon to horizon in a vertical plane perpendicular to the mountain range. On the basis of visual observations and photographs from a sky camera mounted on the lidar, received lidar echoes were attributed to returns from a visually clear sky, from tenuous (visually transparent) clouds, or from dense (visually opaque) clouds. The atmospheric backscatter signals from each transmitted pulse were monitored as a function of range on an oscilloscope and recorded on Polaroid photographs. The individual lidar backscatter signals from each complete vertical scan were used to construct by a hand-analysis technique two-dimensional cross sections of the atmosphere analogous to the familiar RHI presentation of weather radar practice. The cross sections were constructed by indicating along each line of elevation the range interval over which a significant lidar backscatter signal was recorded: solid lines represent returns from visible cloud, and dashed lines represent returns from subvisible cloud, haze or dust. The spatial structure of backscatter signals associated with visible clouds is emphasized by shading. Details on the thickness and layered structure of the recorded echoes were obtained from a dual-beam oscilloscope display that showed the lidar echoes on an expanded time (range) scale.

The firing-rates of the Mk V and Mk VII air-cooled

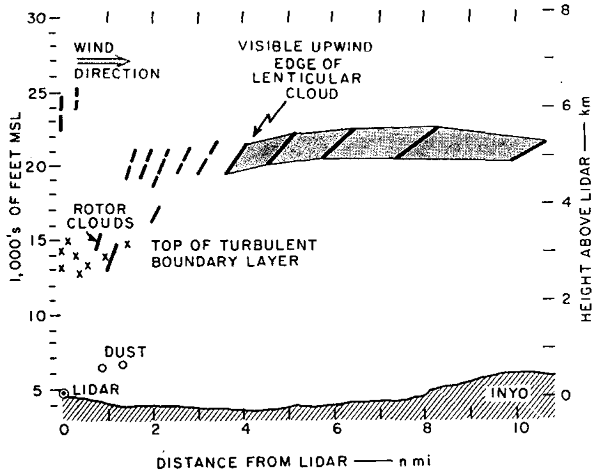


FIG. 2. Vertical cross section (looking toward north) of visible cloud structure (solid lines and shading) and subvisible structure (dashed lines) observed by lidar over Owens Valley during Sierra-wave conditions on 20 March 1969, 1627–1649 PST. Crosses indicate lidar-detected upper boundary of turbulent boundary layer.

ruby lidars do not exceed 1 pulse min^{-1} when the lidars are operated over extended time periods under adverse field conditions. Consequently, the lee-wave structure analyzed from the data of horizon-to-horizon scans has a low-time resolution and can only be interpreted in terms of the gross, time-integrated features.

A greatly improved lidar system, the SRI/EPA Mk VIII lidar, has recently become available for field use. This ruby system is liquid-cooled, has a high pulse-repetition rate (20–30 pulses min^{-1}), and includes an automatic programmed scanning and firing capability. The backscatter data received after each lidar pulse transmission are stored on a magnetic disc. After each horizon-to-horizon scan the back scatter data can be "played back" on an oscilloscope in the form of a range-corrected, intensity-modulated RHI display. Thus, vertical cross sections of atmospheric structure can be generated in near real time. The applicability of this highly automated system to mountain-wave observations[2] was explored in the lee of Mt. Rose, Nevada, during a one-week period in February 1971.

3. Lidar observations made in the southern Sierra Nevada

The data collected in the southern Sierra Nevada during March and April, 1969, extend and clarify the observations made by Collis *et al.* (1968) in 1967. For example, of special interest were the observations made at Independence on the afternoon of 19 February 1967 in an easterly flow. To the eye, although patches of altocumulus clouds were apparent over the Inyo Mountains, many of the lidar echoes were recorded under visually clear, blue-sky conditions. When analyzed, these echoes revealed a layer or boundary at the height of the observed altocumulus clouds that appeared to be spatially continuous. The interesting features were the way in which undulations in this subvisible layer occurred and, in particular, the indications of occasional interruptions in this lidar-detected boundary. The interruptions were thought to indicate a breakdown of the wave motion, which, in turn, could be associated with turbulence or with the development of a turbulent rotor region. These interpretations are clarified by the observations made near Lone Pine on 20 March 1969 during westerly flow. The spatial distributions of the lidar echoes from the two series of observations are compared in Fig. 1. On 20 March 1969 (Fig. 1b), the layer of lidar echoes detected in the visually clear sky between the altostratus wall to the west of the lidar site and the lenticular cloud to the east is similar to that detected during the lidar experiment at Independence on 19 February 1967 (Fig. 1a). From visual observations made at the time of lidar data collection and from the examination of individual lidar traces, it was evident that the "clear air" echoes of 20 March 1969 were connected with thin bands of tenuous clouds that were seen to emerge from the altostratus. It is believed that they represent concentrations of cloud particles (possibly ice crystals) near the subvisible range that are advected downwind along the descending air trajectory of the lee region into the ascending trajectory associated with the lenticular cloud over the Inyo Mountains. The "clear air" discontinuities in the lidar data of 19 February 1967 could be interpreted similarly as subvisible concentrations of cloud particles that are advected in the easterly air flow from the orographic altocumulus clouds over the Inyo Mountains. The undulating appearance of this subvisible layer of particulates is believed to reflect a small-amplitude lee-wave development. The development of a rotor zone is heralded by the appearance of echo clusters (indicated by open circles in the analyses of Fig. 1) below the level of the developing wave motion. These clusters arise from dust and variable dust concentrations in the turbulent boundary layer. As the rotor region intensifies, rotor clouds begin to appear.

Fig. 2 illustrates the atmospheric structure 7 n mi downwind from the Sierra crest analyzed from lidar backscatter signals recorded on 20 March 1969 at a time shortly after that of Fig. 1b. Noteworthy is the appearance of rotor clouds near the upwind edge of the visible lenticular cloud, a frequently observed feature that differs from that associated with the classical lee-wave streamline pattern computed by Scorer and Klieforth (1959). The rotor clouds are located along the upper boundary of the turbulent boundary layer (TBL). The height of the upper boundary (indicated by crosses in Fig. 2) varies considerably

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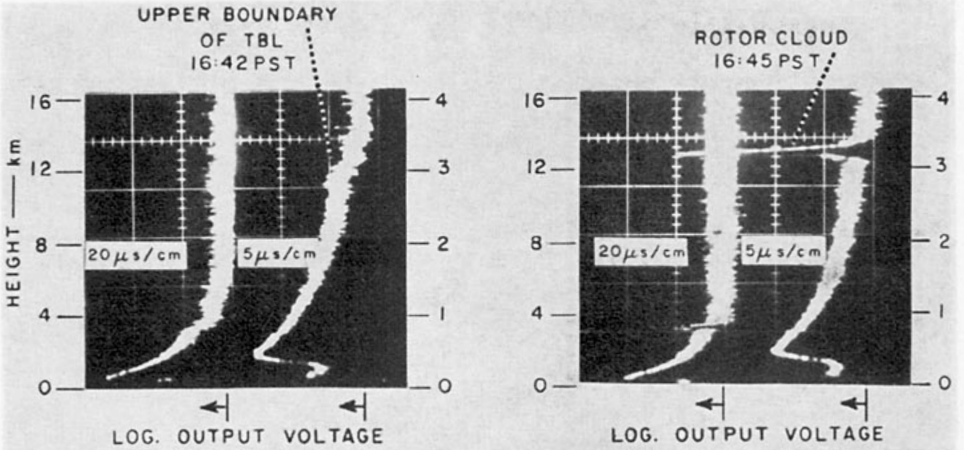
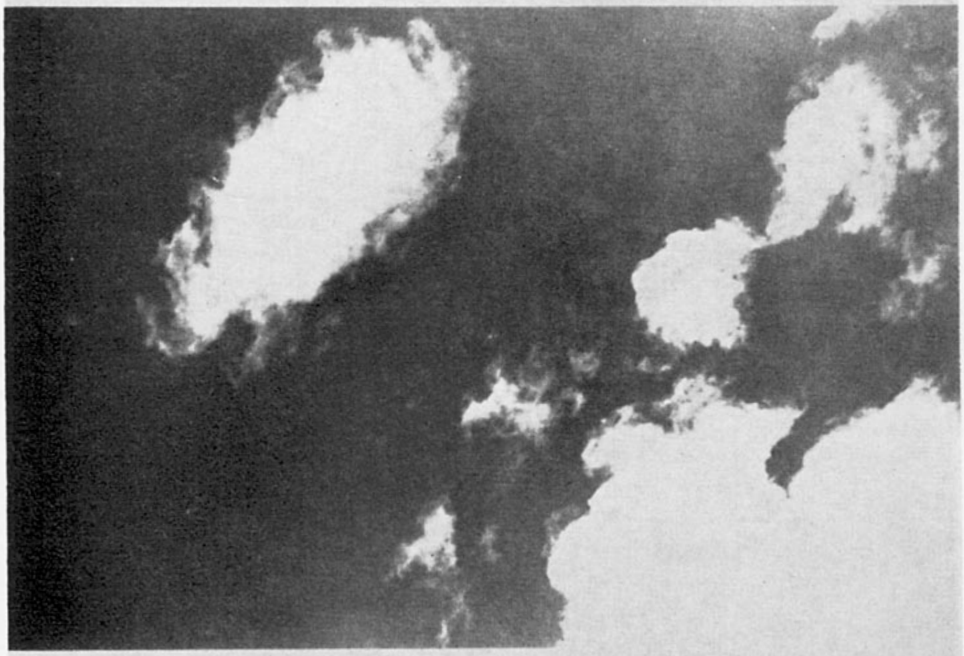
[2] The Mk VIII lidar, the construction of which was partly supported by the Division of Meteorology of the Air Pollution Control Office, Environmental Protection Agency, was used by permission of that Agency.



(a) DUAL-BEAM OSCILLOSCOPE DISPLAYS SHOWING THE UPPER BOUNDARY OF THE TURBULENT BOUNDARY LAYER AND THE ROTOR CLOUDS AS IDENTIFIED BY LIDAR



(b) PHOTOGRAPH OF THE LIDAR-DETECTED ROTOR CLOUDS

FIG. 3. Data sample on turbulent boundary layer (TBL) observed near Lone Pine, Calif., on 20 March 1969.

in space and time. Fig. 3 shows, on a dual-beam oscilloscope display, the top of the turbulent boundary layer (at 1642 PST) which is identified in the lidar data by a decrease in the atmospheric backscatter signal with height, most likely due to a decrease in the dust and aerosol concentration. Also shown are an example of the large backscatter signal received from the rotor clouds at 1645 and a photograph of these rotor clouds as they were visually observed.

Fig. 4 shows the wave-cloud structure and the turbulent boundary layer as analyzed from lidar data obtained during a moderate wave development on 18 March 1969. The lidar data were collected during a time period when a T-33 aircraft from the Flight Research Facility of NASA at Edwards explored the area of wave activity. The indicated subjective turbulence reports are typical of what the research aircraft encountered during the 1969 experiment in the southern Sierra Nevada: moderate turbulence was always encountered in the turbulent boundary layer under the wave clouds where the lidar detects variable dust concentrations; and the tropospheric layer of wave clouds generally presented no more than very light turbulence, which is compatible with the high degree of laminar flow reflected by the lidar-detected wave cloud structure. Fig. 5 shows a time sequence of representative samples of lidar backscatter signals received from the wave cloud of Fig. 4 and obtained at elevation angles

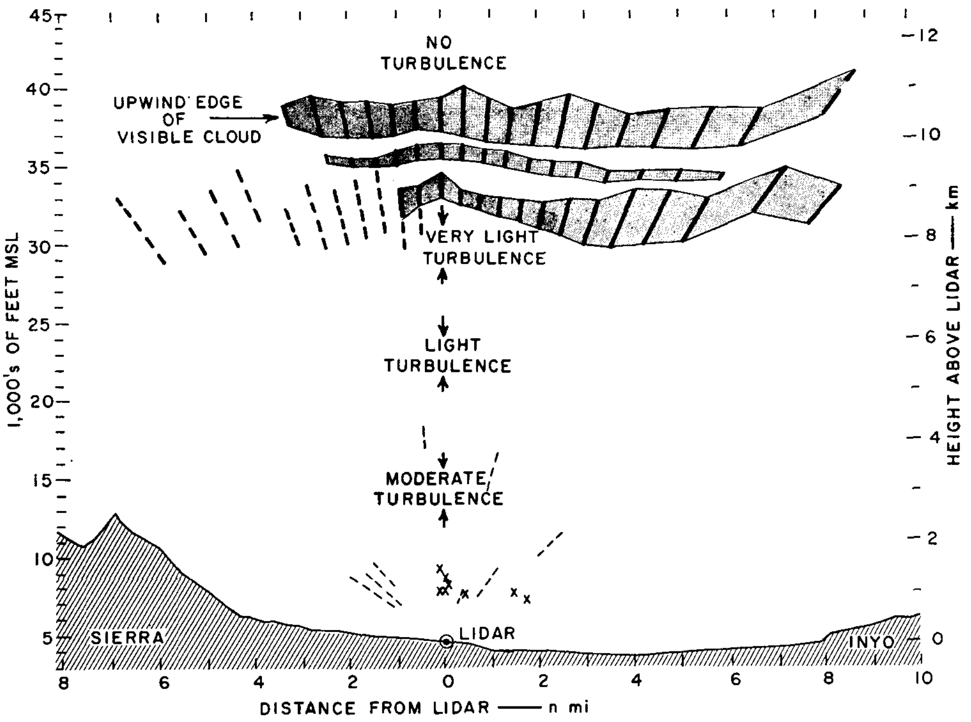


FIG. 4. Wave-cloud structure and turbulent boundary layer analyzed from lidar data obtained during Sierra-wave conditions near Lone Pine, Calif., on 18 March 1969, 1338–1410 PST. Turbulence reports from NASA research aircraft.

near the zenith. Initially (1324 PST), the lidar detected two separate layers. Judging from the intensity and shape of the lidar signal, the two layers have quite different backscatter properties. It can be demonstrated that the average range-corrected backscatter from the upper layer is about 15 times as large as that from the lower layer. Since the radiosonde data indicated temperatures below −50C at the heights of both lidar detected layers, these layers most likely represent ice-crystal clouds of widely different number density and/or size distribution.

From 1350 on, the lenticular cloud is characterized in the lidar data by a sharply defined three-layered structure. The lidar signals near 6000 m (23,000 ft MSL) recorded at 1424, are associated with rotor clouds that developed under the base of the lenticular cloud.

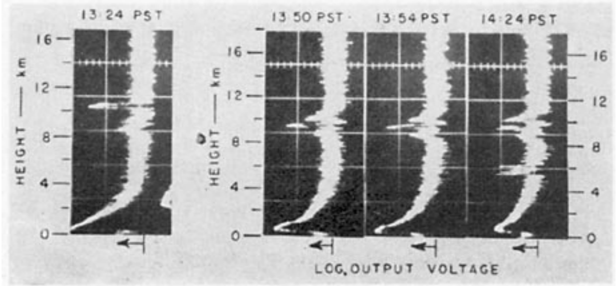


FIG. 5. Time sequence of lidar backscatter signals received from the lenticular cloud of Fig. 4.

Although rawinsonde data were used in the interpretation of the lidar data, their usefulness was limited by the fact that the balloon was released *at* the lidar site. Consequently, at levels above the rotor region and in the upper troposphere the pertinent rawinsonde data were no longer coincident in space with the lidar data.

4. Lidar observations made in the northern Sierra Nevada

Under the assumption that the chances of a high-velocity jet stream and subsequently a strong lee wave, would be greater in the northern Sierra Nevada, the lidar equipment and a supporting rawinsonde unit[3] were moved to Reno, Nev., on 10 March 1970. The road development in this area makes it possible to operate the rawinsonde unit at a site up-wind from the location of the lidar. The 16-ft covered van housing the Mk VII ruby lidar and its data-recording equipment was parked on a site 6 mi ENE of Mt. Rose (10,778 ft MSL) and 8 mi SW of Reno.[4] During strong westerly or southwesterly airflow the lidar would thus be located under the primary crest of the Mt. Rose lee wave. The rawinsonde unit was placed at the Truckee-Tahoe Airport, 18 mi WSW of the lidar site.

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[3] The rawinsonde unit used was a rental unit (Model RD-65 Rawinsonde Receiver and Recorder) made by Weather Measure Corporation, Sacramento, Calif.

[4] The use of the site (elevation 5640 ft MSL) was granted to SRI by the University of Nevada.

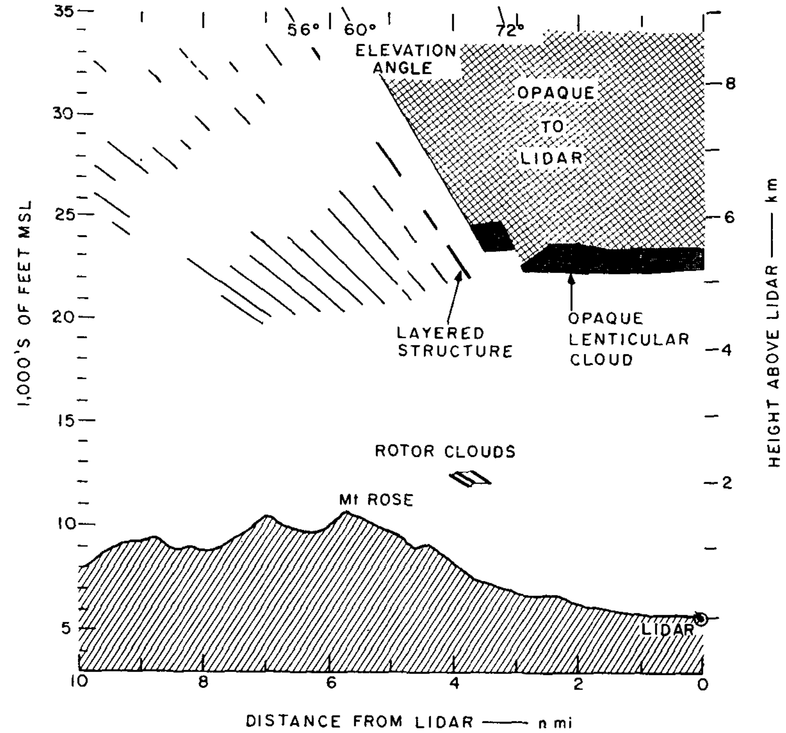

Fig. 6. Vertical cross section (looking toward north) of atmospheric structure analyzed from lidar data during Sierra-wave conditions in the lee of Mt. Rose, Nevada, on 12 March 1970, 1816–1845 PST. Dark shading identifies extent of lenticular-cloud penetration by the lidar.

a. Observations of 12 March 1970

On 12 March 1970, lidar observations were collected from 1500 to 1930 PST when lenticular clouds were present. Fig. 6 shows a vertical cross section of the lidar-observed atmospheric structure. The lidar was fired at intervals in elevation angle selected in such a way as to obtain equal horizontal spacing between the successive lines of sight (and subsequently between the recorded backscatter signals) of about 1600 ft at 25,000 ft MSL. The location of the primary lenticular cloud overhead and to the west of the lidar site is indicated by the data. Because of rapid extinction of its pulse energy, the lidar penetrates the visible lenticular cloud for only a limited distance (indicated by dark shading). Thus, in this case, the lenticular cloud prevented direct probing of the upper troposphere above. The broad layer of backscatter signals recorded between 20,000 ft and 25,000 ft MSL over Mt. Rose, was associated with transparent clouds that had the visual characteristics of cirrus. The presence of such a transparent layer upwind from a visually opaque lenticular cloud was observed frequently by the lidar (see also Figs. 1, 2 and 4). Of interest is the optical change from the multiple layers of transparent cloud (at 56° elevation) to the opaque lenticular cloud (at 60° elevation) over a horizontal distance of only 1600 ft. The lidar echoes above 30,000 ft MSL may have been connected with high-level aircraft contrails that were seen within the field of view of the lidar receiver. Fig. 7 shows actual lidar backscatter signals received from the opaque lenticular cloud at 60° and 72° elevation angles and from the multiple-layered cloud at 56° elevation. From a dual-beam oscilloscope display, the lidar signals can be examined for detail on an expanded (5 μsec cm^{-1}) scale. The above-mentioned large spatial change in backscatter characteristics from the multiple layers of transparent cloud to the visually opaque lenticular cloud over a horizontal distance of only 1600 ft is evident from a comparison between the lidar signal returns at 56° and 60° elevation angles. The expanded (5 μsec cm^{-1}) traces suggest that the large-amplitude return signal recorded at 60° that identified the upwind edge of the lenticular cloud lies within a layer of relatively low return signal similar in character to that recorded at 56°. If, below 25,000 ft MSL, the wave-cloud layer shown in Fig. 6 consisted of supercooled water droplets (temperature at the level was ~ -30C), then the large difference in intensity of the lidar backscatter signals suggests that the visible lenticular cloud resulted from a rather explosive growth in drop size and/or drop concentration within the apparent laminar flow pattern.

b. Observations of 13 March 1970

On March 1970, rawinsondes were launched from the Truckee-Tahoe Airport at 1030 and at 1345 PST;

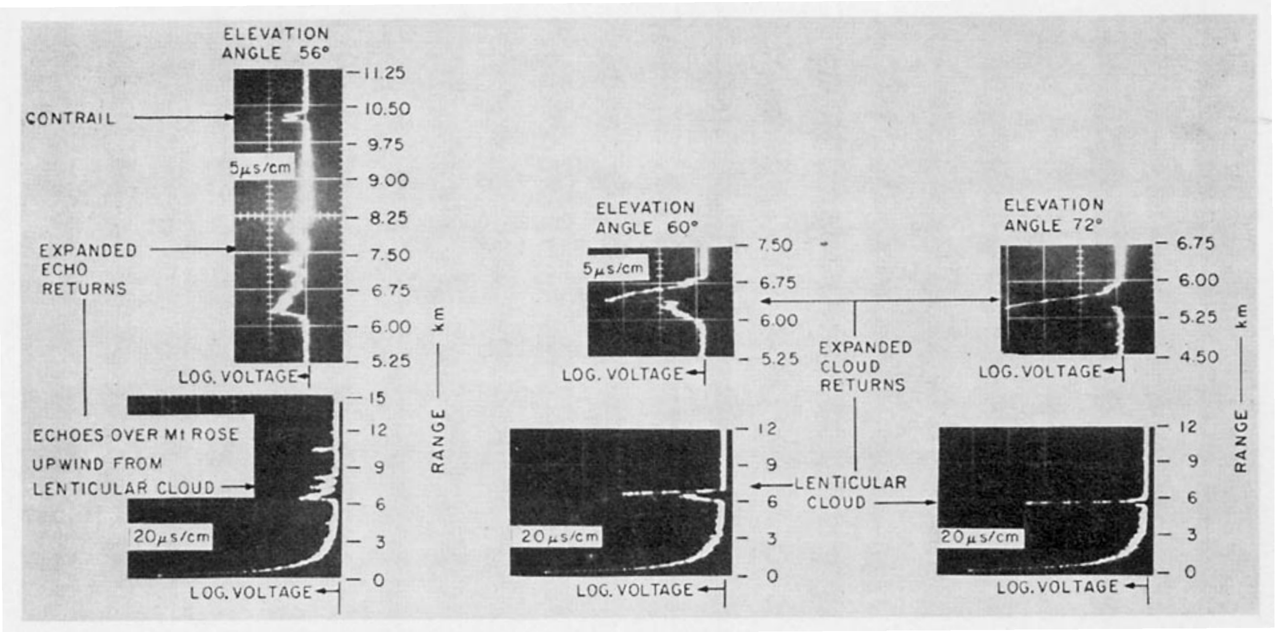

FIG. 7. Examples of lidar backscatter signals recorded from the opaque lenticular cloud of Fig. 6 at 60° and 72° elevation angles, and from the multiple-layered transparent cloud at 56° elevation angle.

lidar data were collected from 0900–1100. No lenticular clouds were observed during this time period, but an extensive coverage of high clouds was present with areas of rapidly developing and decaying billows. Fig. 8 shows the lidar data and the comparative rawinsonde data. The exact position of the radiosonde balloon as it came across the field site after the 1030 launch is indicated also. The lidar echoes that relate to the observed billow structure appear to be located in a layer of near super-adiabatic lapse rate capped by a temperature inversion. Such a thermal stratification in conjunction with the observed vertical wind shear has been discussed by Sekera (1948) in connection with the development of short gravitational waves of the Helm-

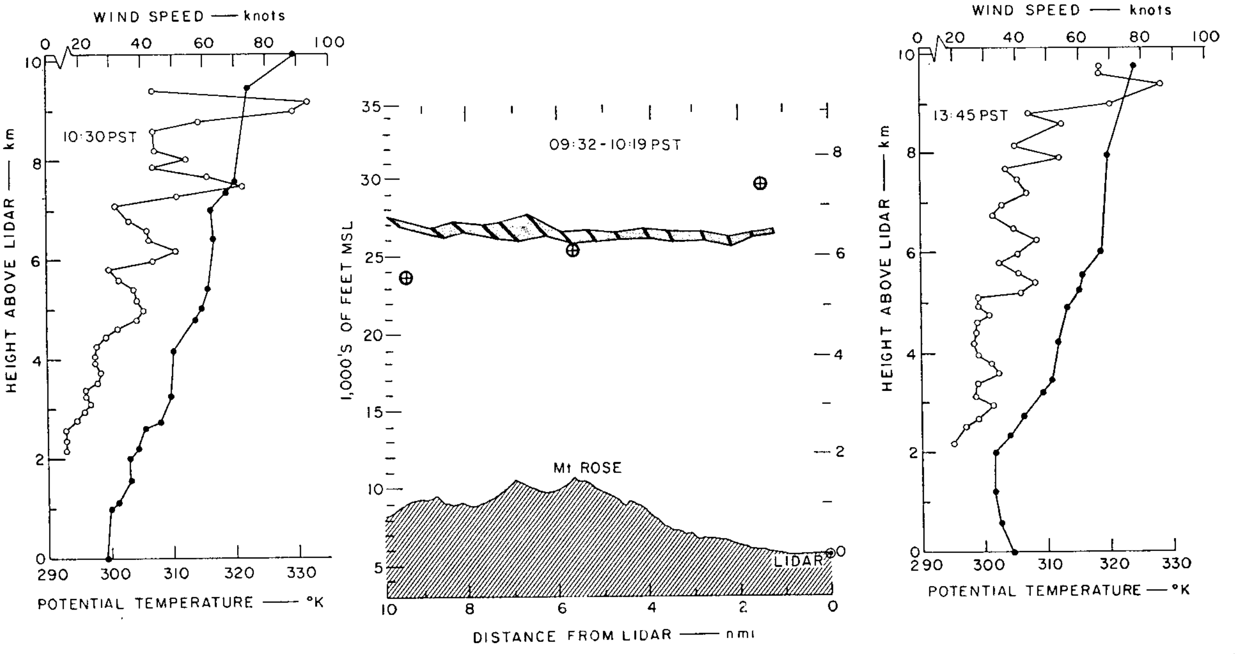

FIG. 8. Rawinsonde data (solid dots, potential temperature; open circles, wind speed normal to mountain range) with the height and spatial extent of the lidar echoes observed during the occurrence of billow clouds over Mt. Rose, Nevada, on 13 March 1970, 0932–1019 PST. Circles indicate position of radiosonde balloon as it crossed the field site after 1030 launch from Truckee-Tahoe Airport.

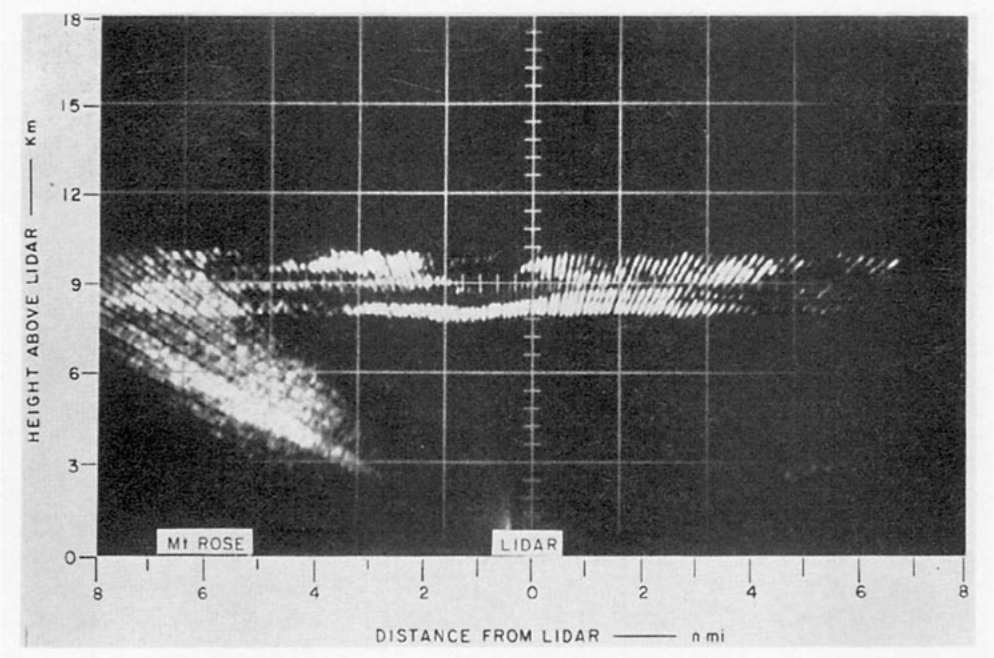

Fig. 9. Cathode-ray-tube display of the atmospheric structure detected by the Mk VIII lidar while scanning through 140° angular sector at intervals of 1°: Mt. Rose, Nevada, 9 February 1971, 1310–1317 PST.

holtz type. Such waves are recognized as an intermediate stage between laminar flow and fully developed turbulence. The observed layer of particulate matter was transparent to the lidar pulse energy and no echoes were received from above or below. Apart from a slight undulation in the layer over Mt. Rose, no clear-cut identification of billow cloud structure can be made on the basis of the lidar data alone. It is obvious that the observed short-wavelength waves must be investigated with a higher pulse-rate-frequency lidar than was used. Also the ability to rapidly scan at very small intervals in elevation angle ($\leqslant 1°$) seems necessary. It is not known whether or not turbulence was actually present in the layer of billow clouds at the time of lidar probing. It is noteworthy, however, that the 1345 PST rawinsonde data show a near-adiabatic lapse rate throughout a broad layer centered at the level of the earlier-observed clouds. This layer could have resulted from the effects of turbulent mixing (Pao and Goldburg, 1969).

c. Observations of 6–13 February 1971

A final experiment was carried out in the lee of Mt. Rose, Nevada, during the week of 6–13 February 1971 for the purpose of exploring the applicability of the SRI/EPA Mk VIII lidar system to mountain-wave observations.

The primary differences in the Mk VIII lidar from its predecessors are:

1) The Mk VIII is a liquid-cooled system with a stable firing rate of one pulse per 2–3 sec.

2) The Mk VIII has the capability of being automatically scanned in equal elevation (or azimuth) increments at selected firing rates.

3) The transmitter and receiver are coaxial.

4) The receiver has a disc storage memory with playback features.

5) A continuous-view two-dimensional intensity-modulated cathode-ray-tube (CRT) presentation in radar RHI or PPI fashion is incorporated.

Fig. 9 shows a CRT display of the atmospheric structure as observed with the Mk VIII system in the lee of Mt. Rose. Observations were made from the same location as in the earlier experiment. The cross section was obtained in about 7 min by selecting a firing rate of 1 pulse per 3 sec per 1° interval in elevation angle while scanning from Mt. Rose in the west toward the east. Multiple-layered structure in observed cirrus clouds is evident. The brightness recorded in the direction of Mt. Rose is due to the high sky background level near the position of the sun.

Although only insignificant wave action was present during the observation period, the lidar data clearly demonstrate the superior performance of the system and its potential in mapping atmospheric wave structure in near real time.

5. Conclusions

The data collected during the study extend and clarify the lidar observations of Sierra-wave conditions made initially by Collis *et al.* (1968) at Independence, Calif., during February and March, 1967. The lidar can outline various important features of the atmospheric structure during mountain-wave conditions. In particular, it can provide detailed information on the location, spatial extent, layered structure, and optical characteristics of the lenticular clouds, and on the development and location of rotor clouds. A ground-based lidar can detect temporal and spatial variations in the vertical extent of the lower turbulence zone (the rotor region under the lenticular clouds) which can harbor moderate and severe turbulence associated with convection and rotor flow. This information can be provided by monitoring the lidar echo activity that arises from the presence of rotor clouds and from the presence of dust and variable dust concentrations.

At all times, the lidar data showed lenticular cloud structure reflecting highly laminar flow. Thus, a probable non-occurrence of turbulence could be inferred from this type of lidar-detected cloud structure. The upper troposphere above the wave clouds could not be explored directly by the ground-based lidar because the lenticular clouds were frequently opaque to the lidar pulse energy, especially during low-level wave development, when the wave clouds consisted of water droplets. During a period when no lenticular clouds were observed but extensive billows indicated wave activity, the lidar data showed an undulating layer of particulates at an altitude where rawinsonde data showed temperature and wind conditions conducive to the development of Helmholtz waves.

It is concluded that, in conjunction with other probes and programs, a ground-based lidar can complement and extend the data required for mesoscale analysis of mountain-induced gravity waves and turbulence.

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