Tellus (1990), *42B*, 211–216

Lidar observations of the horizontal orientation of ice crystals in cirrus clouds

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(Manuscript received 10 October 1988; in final form 4 July 1989)

ABSTRACT

A scanning lidar system has been used at Aberystwyth (52.4°N, 4.1°W) to measure the backscatter and depolarization ratios in cirrus clouds. The measurements indicate that the height of maximum occurrence was near 9 km and that about 50% of clouds showed the presence at some height of ice crystals having a near horizontal orientation. The angular dependence of the backscatter about the vertical showed that the maximum tilt angle of these crystals from the horizontal plane was about 0.3°.

1. Introduction

Cirrus clouds have been identified as one of the major unsolved components in weather and climate studies (Bretherton and Suomi, 1983). They contain a significant amount of large non-spherical ice crystals in which plates and stellar forms have been found to predominate at temperatures above −20°C and columns at temperatures below −30°C, as shown by observations at the ground and during aircraft flights (Weickmann, 1945; Magono and Lee, 1966). Furthermore, aircraft observations up to 5.6 km by Ono (1969) indicated that the crystals fall so that the greatest areas of the plates and longest edges of the columns lie parallel to the ground, such that the resistance of the air is a maximum. The reflection of sunlight from such orientated plates and columns is believed to produce certain optical phenomena in the sky (Greenler, 1980). Their presence has also been demonstrated in laser radar (lidar) measurements by Platt (1977), Platt et al. (1978) and Sassen (1984) of backscatter and depolarization at vertical and near vertical incidence, and by Gibson et al. (1977) of backscatter and extinction at different angles of incidence. The observations by Platt (1977), Platt et al. (1978), and Sassen (1984) referred to heights of 4.6–5.6 km, 2.4–3.0 km, and 4.7–5.1 km, respectively, the corresponding temperature ranges being −12°C to −20°C, −9°C to −13°C, and −17°C to −20°C. The three sets of measurements were interpreted in terms of ice crystal plates. The observations by Gibson et al. (1977) referred to heights of 10–12 km, and therefore related to lower temperatures characteristic of the upper troposphere, and were interpreted in terms of ice columns.

Asano (1983) has shown that the reflection and transmission properties of cirrus clouds with optical depths equal to or less than unity depend significantly on whether the ice crystals are orientated randomly in three-dimensional space or in horizontal planes. Thus information on the proportion of crystals showing horizontal orientation is relevant to calculations of atmospheric heating rates involving cirrus. Furthermore, the observation of orientated crystals at different heights, and therefore temperatures, relates to the habit of such crystals. Finally, the changes in backscatter for laser beam directions about the vertical can provide information on the distribution of ice crystals about the horizontal plane. The present paper describes lidar measurements at Aberystwyth (52.4°N, 4.1°W) which show that at any height in the cloud there is a 50% chance that ice crystals orientated within small angles of the horizontal plane are present. By analogy with laboratory studies it is suggested that these crystals might be fluttering about the horizontal plane.

2. Equipment

The lidar system makes use of a Neodymium/Yag laser with a frequency doubling crystal to produce plane-polarized 15 ns pulses of about 250 mJ energy at 530 nm with a repetition rate of 10 Hz. The laser output is expanded by a telescope which reduces the laser divergence to 0.1 m rad and a Cassegrain-type receiving telescope, with 0.6 m diameter primary mirror, focuses light on to a field-stop aperture of variable diameter followed by a collimator. The axes of the laser transmitter and the telescope are separated by 0.8 m to avoid overloading the detectors with excess signal from very low heights. The height above which the laser beam overlaps completely the telescope field of view can be varied by adjusting the field-stop aperture thus changing the field of view in the range from 0.3 to 0.8 m rad. The collimated beam passes through a 1 nm bandwidth interference filter which with the small field of view provides an effective reduction of background light, thereby permitting daytime operation. The beam is then directed on to a plain glass beamsplitter and passed to one of two EMI 9902 photomultipliers fitted with dichroic polarizers for recording the two orthogonal components in the backscatter of the plane-polarized transmitted beam. Photon counting is employed in the data recording with the height resolution being adjustable down to 30 m. The system is capable of scanning in one azimuth, the tracking of transmitter and receiver being ensured by having the transmitter telescope built in to the hollow shaft carrying the receiver mirror. A stepper motor, with suitable gearing, provides incremental changes of 0.1 m rad in the transmitter and receiver beam directions.

3. Observations

Some of the features of cirrus clouds displayed by lidar observations are illustrated in Fig. 1. This shows the height variations of range corrected signal for a set of 1000 laser firings at vertical incidence, represented by full lines, and at 3° from the vertical, represented by broken lines, taken in succession near 21.54 GMT on 5 March 1985. Attention is drawn to the detailed height structure commonly observed with the 30 m resolution of the system. The results for the component polarized parallel to the incident radiation in the two directions reveal enhanced backscatter in the vertical direction compared with that for 3° incidence, particularly in the height ranges 9.8–11.0 km and 6.2–6.7 km, indicated by arrows. It is to be noted that a radiosonde ascent from Aughton (53.6° N, 2.9° W) near midnight indicated temperatures of −60°C and −30°C in these two height ranges, respectively. The corresponding results for the perpendicularly polarized component in the two directions do not show these enhancements in the vertical direction. The height variations of the ratio of the perpendicular to parallel components, called the linear depolarization ratio, can be derived from the measurements of each component, when allowance is made for the beamsplitter efficiency. The height variations of the depolarization ratio for 3° and 0° incidence are presented in Fig. 2. It is seen that for vertical incidence the height range 10.1–11.0 km corresponds to relatively small depolarization ratios, viz. 3% or less; for the range 6.2–6.7 km, the ratio decreases from about 20% at 6.2 km to

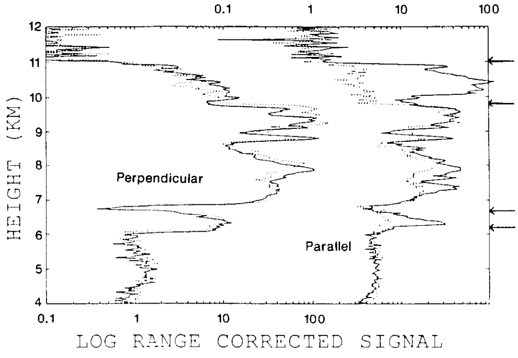

Fig. 1. Height variations of the backscattered components polarized perpendicular and parallel to the incident radiation, near 21.54 GMT on 5 March 1985. The continuous and broken lines refer to transmission at 0° and 3° from the vertical, respectively. The arrows identify the height ranges over which the parallel component shows enhanced returns in the vertical direction compared with those at 3° incidence.

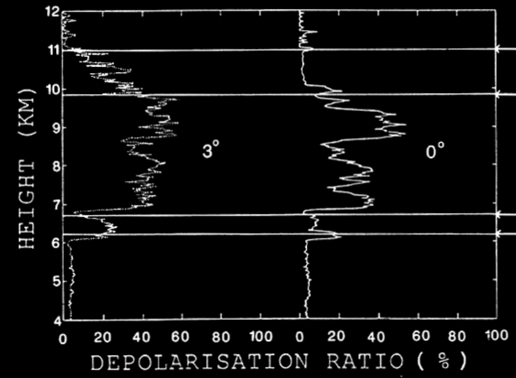

Fig. 2. Height variations of depolarization ratio for data shown in Fig. 1.

values of 5–8% at 6.3–6.7 km. These small depolarization ratios observed for vertical incidence indicates that specular reflection occurred in the corresponding height ranges, with the specularly reflecting faces being horizontal. The values for the two height ranges at 3° incidence are 10–30% and 10–23%, respectively. The increase at 6 km in depolarization ratio to about 20% for both 0° and 3° incidence could indicate the effect of multiple scattering by water droplets as the laser beam penetrates the bottom of the cloud. However, such multiple scattering would be expected to be accompanied by attenuation of the beam whereas an increase in signal is observed for both directions.

The presence of horizontally orientated crystals giving rise to enhanced backscatter of the parallel polarization component is conveniently demonstrated by switching the beam direction sequentially at 10 s intervals between the vertical and 10 m rad from the vertical and using the returned signal to intensity modulate a cathode ray display. The example shown in Fig. 3 relates to

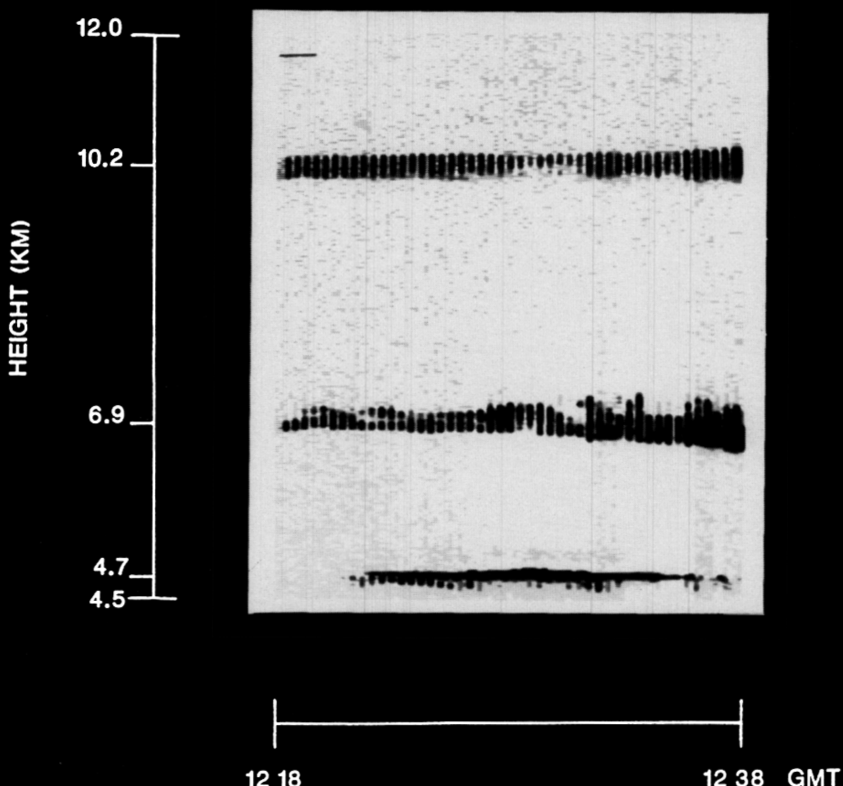

Fig. 3. Observations on 24 July 1987 of the backscatter of the parallel polarized component when the beam direction was switched sequentially between the vertical, represented by the white regions, and 10 m rad from the vertical, represented by the dark regions.

the period 12.18 to 12.38 GMT on July 1986, the white and dark regions corresponding to vertical and off-vertical beam directions, respectively. It is seen that orientated crystals were observed simultaneously in three discrete layers, near 4.7 km, 6.9 km and 10.2 km. Radiosonde measurements at Aughton showed the corresponding temperatures to be −9.0°C, −22.5°C and −46.5°C, respectively. The overall results deduced from 20-min samples using this approach for the majority of days free of low-lying cloud in the period July 1986 to May 1989 are shown in Fig. 4. This shows the total number of times cirrus clouds observed in different height ranges and also the number of times crystals having a preferred horizontal orientation were detected in different height ranges. It is seen that the height of maximum occurrence was near 9 km and there was about a 50% chance that orientated crystals were present at any height. From radiosonde data, it was found that the heights of occurrence of the orientated crystals corresponded to a temperature range of about −5°C to −70°C. Corresponding lidar measurements at 38°S in Australia by Platt et al. (1987) showed the presence of orientated crystals at temperatures greater than −40°C, especially in winter, when 57% of observations in the temperature range −20°C to −25°C, and 46% in the range −30°C to −35°C, displayed such crystals which were interpreted as hexagonal plates.

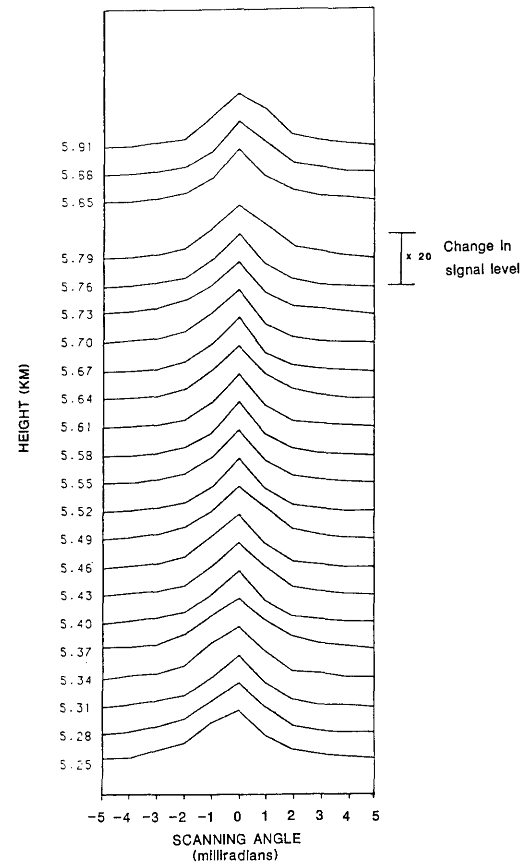

Fig. 5. Variations at different heights of the normalized backscatter of the parallel polarized component during scans of beam direction about the vertical, near 23.00 GMT on 23 September 1985. The change of backscatter by a factor of 20 at any height is illustrated.

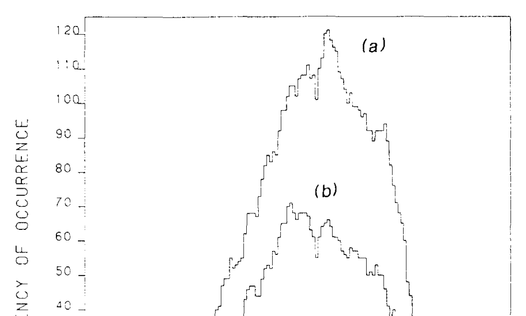

Fig. 4. Heights of occurrence (a) of all cirrus clouds observed and (b) of crystals with a preferred horizontal orientation, in the period July 1986 to May 1989.

The data for heights below 3 km in Fig. 4 include days in spring, summer and winter months. It is believed that they relate to snowflakes near the top of the melting layer as identified in polarization radar measurements in southern England which also show some degree of preferred horizontal orientation (Hall et al., 1984).

To examine the deviation of crystal orientation from the horizontal, observations were made of the backscatter for angular steps of 1.0 m rad either side of vertical. Fig. 5 shows the variation of backscatter with scan angle for the component polarized parallel to the incident radiation for individual heights at 30 m intervals in the range 5.25–5.91 km near 23.00 GMT on 23 September 1985. It can be seen that for each height the backscatter decreases by a factor of about 20 between the vertical direction and ± 5 m rad from the vertical, the actual angular dependences being similar. The absence of any variation for the perpendicular polarization component during the angular scans indicates that spectular reflection at normal incidence occurs for off-vertical angles up to 5 m rad, implying the presence of crystals orientated at similar angles (0.3°) to the horizontal plane.

4. Discussion

Laboratory measurements have shown that temperature is the principal factor determining crystal habit but that humidity conditions also have an influence (Kobayashi, 1961; Mason et al., 1963). Thus for temperatures above about -8°C and below about -25°C column-type crystals have been observed whereas in the intermediate temperature range plate-type forms predominate; for humidity conditions close to ice saturation the columns are characteristically short and the plates thick; for conditions of greater vapour density the columns are longer and hollow, and the plates become thin and take sector and dendritic forms. Although uncertainties arise in establishing the temperature and humidity at which natural ice crystals grow and acquire their shape, Pruppacher and Klett (1978) have noted that there is basic agreement between laboratory observations of crystal habit and the observations of crystals in clouds, as summarized by Magono and Lee (1966). However, the cloud observations also show more complicated forms, such as combinations of columnar crystals in which individual columns might be bullet-like.

On the basis of the laboratory and cloud observations, it might be expected that the crystals giving specular reflections at heights up to the middle troposphere in the present study would be predominantly of plate and sector-plate form and those at greater heights, near the tropopause, of columnar form. Takano and Jayaweera (1985) and Takano (private communication, 1988) have demonstrated theoretically that hexagonal plates and columns randomly orientated in a horizontal plane give rise to enhanced backscatter of the parallel polarized component and very low depolarization ratios for vertical incidence.

Sampling experiments employed by Mossop et al. (1967) and Heymsfield (1975) have shown the presence of hexagonal plates at heights corresponding to temperatures of -33°C and -35°C and it is possible that plate forms could also have contributed to the enhanced returns from heights near the tropopause, where the temperatures are still lower, in the present study. In this connection, aircraft observations by Heymsfield (1986) in a cirriform cloud between 16.2 and 16.7 km near the equator, where the temperature was near -83°C, showed the crystal habits to be a 50% mixture of trigonal plates and columns. Evidence for such trigonal ice forms at such low temperatures has been obtained in laboratory experiments by Yamashita (1973).

The maximum tilt angle of ice crystals from the horizontal of about 0.3° indicated in the present study and of 0.5° found by Platt et al. (1978) are smaller than the values derived from observations of the circumzenithal arc by McDowell (1979), about 1°, and of light pillars by Sassen (1980), up to 3°. Information relating to the behaviour of crystals descending in the atmosphere has been obtained from laboratory studies of discs and cylinders falling freely in viscous liquids (Willmarth et al. 1964; Jayaweera and Mason, 1965), the behaviour being characterized in terms of the Reynolds number, $\mathrm{Re} = vd/\nu$, where d represents the diameter of the particle falling with a velocity v in the fluid of kinetic viscosity ν. Willmarth et al. found that thin disks generally assume a horizontal attitude in a quiescent fluid for the range of $1 < \mathrm{Re} < 100$. Sassen (1980) showed that light pillars were only observed for plate-like crystals for which Re was within this approximate range but that the ability of these crystals to maintain horizontal orientation was a function of Re. Crystals for which $\mathrm{Re} \approx 10$ (diameter ≈ 0.5 mm) showed the most perfect alignment, with a tilt angle of 0.5°, but those corresponding to $\mathrm{Re} \approx 1$ (diameter ≈ 0.15 m) and $\mathrm{Re} \approx 100$ (diameter ≈ 3.5 mm) each showed tilt angles of 3°. These results of Sassen (1980) would suggest that the relatively small values of maximum tilt angles found in lidar measurements correspond to a small range of Re values and therefore to a small range of crystal diameters.

5. Acknowledgement

We are indebted to the UK Meteorological Office for the award of a studentship to one of us (JCC) by the Gassiot Grants Committee and for the provision of radiosonde data.

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