Ice crystals and solar halo displays, Plateau Station, 1967

BY

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From December 1966 through January 1968 an extensive micro-meteorological programme was operated at Plateau Station, 79°15'S, 40°30'E, at an elevation of 3625 m. This programme's main goal was the study of energy fluxes in the surface inversion and in the snow to a depth of 10 m. Net accumulation and surface density measured in this connection was 9.1 cm snow per year at 0.30 g/cm³ in 1967. Of all positive contributions to the net accumulation, i.e. precipitation, direct condensation of moisture on the surface and import by drift snow, the substantial part is made up by precipitation of ice prisms from cirrus clouds or from cloudless skies. This ice crystal precipitation was observed on 317 days in 1967, with frequency maxima in spring and fall (every day) and minima in January (14 days) and June (23 days). The intensity varied from an intermittent fall of single crystals to strong uniform precipitation that could decrease atmospheric transparency by 8 per cent.

Although no systematic study of the precipitated crystals was undertaken it is possible to obtain some information on their physical condition. The structure of ice crystals is mainly determined by air temperature and this, together with their orientation, produces a number of distinct solar halo phenomena. The temperature inversion was recorded in detail on a
32 m high tower, complemented by balloon soundings during the winter night. A typical profile is a strong inversion of 40°C in winter and 10 to 20°C in summer between the surface and about 100 m. From 100–1000 m there follows a generally much weaker gradient or nearly isothermal layer. Temperatures ranging from —86°C to —18°C provide for very high stability of the inversion layer.

The principal source of precipitation is condensation of advected moisture in the region of the maximum temperature gradient in this layer. Owing to the high stability, the discontinuity between advected and surface air may be as sharp as 20°C over 4 m. A second mechanism of ice crystal production is a local cycle during the summer period, when evaporation from the snow during strong irradiation is followed by cooling and condensation at night. No definite correlation of this cycle with the surface heat budget could be found, but ice crystals generally start falling before midnight and continue for 6 to 12 hours. The height and strength of the nightly inversion depend on the duration of insolation, and the thickness of the layer which is active in this cycle varies accordingly. Around the equinoxes it is most marked and thereby contributes to the spring and fall maxima of precipitation, while the same maxima are caused by increased cyclonic activity in the case of coastal stations. The third source of ice crystals is clouds, precipitating either directly, or by repeated condensation when particles falling from cirrus clouds evaporate and then recrystallize in the inversion layer.

In the course of the year’s observations six main crystal types were recognized, four of which contributed to the formation of halo phenomena. Each type is associated with a certain temperature range as observed by various investigators (Nakaya, 1951): (1) Granular snow crystals of 0.5 to 1 mm diameter originating from dendrites by accretion of water droplets. These occurred only in the presence of low level clouds and did not produce halos because of their irregular shapes. (2) Stellar dendrites formed in temperatures between —15°C and —20°C. These crystals were observed only three times during the summer, and did not exceed 2 mm in diameter. (3) Hexagonal plates between —10 and —22°C. Although their temperature range reaches down far enough they were observed only occasionally. The bulk of the precipitation was made up of the following two groups: (4) Prismatic columns and bullets below —20°C and (5) Compound forms of columns and bullets below —30°C. Both columns and bullets showed air pockets and other irregularities which were observed to increase with decreasing temperature. (6) A very delicate variety of needles about 0.1 mm long was observed occasionally at temperatures below —60°C. These were obviously associated with strong temperature differences, since they occurred mostly before and after cyclonic disturbances when the layering of different air masses is most pronounced. On the surface they gave rise to a fluffy but coherent cover which formed balls of 2 to 5 cm in diameter when picked off obstructions and driven over the snow by the wind. The density of this cover was of
the order of 0.01 g/cm³. The failure of needles to produce halos can probably be attributed to their low temperature of formation and the correspondingly irregular structure of the needles.

Low air temperatures were most favourable to the formation of prismatic crystals, the presence of which is also confirmed by the halo phenomena usually attributed to them. The following table shows the kinds of halos observed at Plateau and their physical causes as explained by Pernter-Exner (1922) and Humphreys (1940):

<table>
<thead>
<tr>
<th>Halo Type</th>
<th>Physical Cause</th>
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<tbody>
<tr>
<td>22° ring</td>
<td>refraction on 60° angle of either prisms or plates falling in random orientation.</td>
</tr>
<tr>
<td>44° ring</td>
<td>refraction on 90° angles, e.g. basal edges of prisms.</td>
</tr>
<tr>
<td>upper and lower tangential arc</td>
<td>60° refraction on prisms with horizontal principal axes.</td>
</tr>
<tr>
<td>parhelia</td>
<td>60° refraction on plates or prisms with vertical axes.</td>
</tr>
<tr>
<td>arcs of Lowitz</td>
<td>60° refraction on crystals with vertical principal axes, oscillating in a plane through the sun and the crystal.</td>
</tr>
<tr>
<td>parhelic circle</td>
<td>reflection from vertical crystal faces.</td>
</tr>
<tr>
<td>sun pillar and undersun</td>
<td>reflection from horizontal crystal faces.</td>
</tr>
</tbody>
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High halo displays in cirrus clouds were restricted to 22° rings with upper or lower tangential arcs and occasional whitish parhelia. The crystals can be of various types, of generally random orientation. Whenever the refracting edge of a crystal is tilted away from the normal to the plane through sun and observer, the refracting angle or the effective refractive index changes. This causes a gradual increase of the angle of minimum deviation and therefore a blurring of colours so typical of high level halos, where normally only the innermost, red ring is preserved.

Low level halos are produced by crystals floating in the calm, stable inversion layer. Low turbulence and little oscillation of crystals provide for much better resolution of colours than in turbulent high level clouds. Aerodynamic stability is further expressed by the development of halos requiring a preferred crystal orientation before the completion of a 22° ring. Columns will tend to float with their principal axes horizontal, producing the upper and lower sector of a ring, tangent arcs and parhelic circles. Plates, on the other hand, will tend towards vertical alignment of their principal axes and refracting edges which then are inclined to the normal to the plane through sun and observer by an angle which is equal to the solar elevation. The parhelia will therefore move away from the lateral part of the 22° ring with increasing solar elevation and can easily be distinguished from the latter. A deviation of 5 degrees from the vertical will cause a monochromatic ray to change its position in a parhelion by about 10 min of arc, compared to the refractive dispersion of 54 min between red and green. A distinct spectrum in a parhelion is a good
indicator of stable orientation. With increasing turbulence the parhelia will become whitish, then arcs of Lowitz form and only then will the 22° ring be completed in a low level halo. At this stage the parhelia will be connected to the ring that has been described as a circumscribed ellipse by Blake (1961). There may be situations, however, where the simultaneous presence of both coloured parhelia and full 22° rings show the combination of both low and high level halos as in the case of repeated condensation that occurs often during cyclonic activity.

Some speculations can be made about the apparent disagreement between the small number of hexagonal plates found on the surface and the frequent occurrence and brilliant colours of parhelia. The necessary vertical refracting edges could be provided by bullets that are topped by sufficiently regular pyramids. This regularity would not well agree with the actual appearance of the bullets, 60° pyramids moreover would produce a number of other phenomena that were never encountered. On the other hand, Kobayashi actually observed such pyramids in the laboratory at temperatures below −50°C. It is more likely that columns and bullets are compounded into tetragonal or other geometric configurations that allow one crystal to be vertically oriented when the cluster reaches aerodynamic stability. The length of the refracting edge in this case would explain the high brightness of parhelia much better than does the assumption of plates: columns produce more vertical refracting edge per unit volume of air than the same mass of plates. Furthermore, plates with vertical orientation should produce significant sun pillars which were only rarely observed at Plateau. The predominance of columns in the precipitation is confirmed by Kotlyakov (1961) who points out that only above −20°C will the majority of the crystals be plates.

During one particularly complex display direct solar radiation was measured and compared with values obtained during clear conditions one week later. The Figure describes the situation of 17 December with strong ice crystal precipitation from a cloudless sky, and of 24 December, a completely clear day. The upper curve represents direct solar radiation in cal/cm² min, and the lower three curves show the contribution of three spectral regions covering 0.525-2.8, 0.63-2.8 and 0.71-2.7 microns, in per cent of the total intensity. Although the ice crystals attenuated direct radiation by 8 per cent they were too large to act as selective scatterers. Instead, the crystalization diminished the degree of selective scattering by removing a certain amount of water droplets from the atmosphere. Inasmuch as water droplets of small diameter scatter light predominantly in the short wavelengths they deplete the blue part of the spectrum strongest and when they transform into non-selectively scattering ice crystals they increase the contribution to the total spectrum of blue and green wavelengths: the curve labelled OGI shows how the blue and green (λ<0.525 micron) increased 15 per cent during heavy precipitation between 900 and 1100 LST, and only 4 per cent as a result of higher solar elevation on a clear day.
Direct solar radiation and contribution of spectral bands on a day with heavy ice crystal precipitation (17 December), and on a clear day (24 December).

The cloudlike structure that is often seen in low level precipitation might suggest varying mass concentration as it is expected, for example, when driftsnow seeds a supersaturated inversion layer. Pyrheliometric measurement in the direction of the sun, where light from single reflections is not able to strike the instrument showed short time fluctuations not exceeding 1.5 per cent. Since the threshold of brightness contrast for the human eye is 2 per cent, any distinctly visible cloud structure in the low level precipitation can be explained in terms of varying reflection from groups of crystals with different orientation rather than mass distribution.

The application of the laws of optical meteorology has been a helpful addition to the information gained from ground-based work. It is rather unfortunate that it has its limits in the range of temperatures at Plateau Station where the crystal structure is not differentiated enough to make full use of the recorded temperature profiles.

REFERENCES
A study on drifting snow

BY

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ABSTRACT

As part of an investigation aiming to explain the relation between temperature and threshold wind speed for snow drifting, the behaviour of snow particles has been studied by still and high speed ciné photography. No evidence has been found of any surface creep or suspension in the lowest 10 cm above the snow surface where saltation appears to be the sole mode of snow transport by the wind.

Introduction

In a previous study by the authors (Oura et al., 1967) it was shown that the threshold wind speed for snow drifting decreases with temperature from 0 to —7°C and remains constant around 6.5 m sec⁻¹ at a height of 5 m above the snow surface for lower temperatures (down to —23°C). Fig. 1, reproduced from the earlier study, summarizes these results.

For a more accurate estimation of the threshold wind speed, the behaviour of snow particles was studied by photographs taken in still and strobed light, which showed evidence of saltation and confirmed the wind profile measurements for the surface layer. Since then much clearer photos have been obtained of the saltation process which in addition has been filmed with a high speed ciné camera. The new photos are being used to clarify the momentum exchange between the snow particles and the air. Their main features are described in this note.

The motion of snow particles in low drifting snow

The initial stage of drifting snow motion is confined to a shallow layer near the surface. The transportation mechanisms in this layer are said to be “saltation” and “creep”. However, for the saltation mode there has been no direct evidence in regard to whether the particles actually rebound or eject other particles from the snow surface.