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Noctilucent Clouds*

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SUMMARY

Noctilucent clouds are visible during night-time in the summer at high latitudes. They are in the upper atmosphere (typically at 80–85 km altitude) and are very probably of submicron crystals of ice. Forming as they do in a region where the pressure of the atmosphere is one-millionth of that at the ground and where there is very little water vapour, their very existence is at first sight curious.

In this account, the observed characteristics of the clouds, their mode of formation and their use in studying the behaviour of the upper atmosphere are described.

INTRODUCTION

The Harold Jeffreys lectureship was instituted in 1962 by the Council at the time of establishing a Gold Medal in Geophysics. Sir Harold was the first Lecturer (in 1963) and in the past 22 years a series of lectures has followed on subjects ranging from the deepest parts of the Earth to the outermost extensions of the Earth's atmosphere. It is a challenge to be asked to add to this series with a review of what is known about noctilucent clouds.

First, I must attempt to justify the inclusion of such objects of study in the programme of this Society. I rest my case for their inclusion on the words of the motto displayed in the Common Seal of the Society, as set out in the first ByLaw of Section 17 of 1831, *Quicquid nitet notandum* ('Whatever shines is to be studied'). Noctilucent clouds by their very nature and their name shine at night and therefore earn their place among the objects of study by the members of this Society. (They have a better right, in this sense, than do black holes and some other artefacts of our cosmological colleagues.)

The clouds, usually pale blue in colour, may be seen on a clear night in a Scottish summer. A typical example is shown in Fig. 1 and clouds looking like these in daytime would be classified as *cirrostratus*. What sets noctilucent clouds apart is their occurrence in the middle of the night, their very obvious pale blue colour and their disappearance into the dawn close to the onset of civil twilight, when the Sun is 6° below the horizon.

Noctilucent clouds were first recognized as being set apart from ordinary clouds in 1884 (1) and in a series of sightings that followed their return in the summer of 1885 (2, 3). In Germany, the name given them was *leuchtende nachtwolken* but in Great Britain, the rather whimsical name of *silver-blue cloudlets* was used for some time.

*The Harold Jeffreys Lecture for 1985.

The very distinctive patterns that appear in noctilucent clouds were commented on right from the start. Leslie (1) remarks '... weird small cloud forms, at times very regular, like ripple marks in sand, or the bones of some great fish or saurian embedded on a slab of stone.'

Dr Jill Austin has identified pictures of noctilucent clouds in a collection of crayon sketches which is preserved in the Science Museum (4). William Ascroft, the artist whose twilight sketches were published in the Krakatoa Report (5), notes simply that *the light was much prolonged* on the evening of 1885 July 6 from 9·35 to 10 pm. Examination of his sketch shows that there can be little doubt that it is an early record of a noctilucent cloud. A second sketch, dated 1886 July 12, 9·30–9·45 pm ('sustained light; sunset 8·12 pm') also shows a noctilucent cloud.

At midnight, noctilucent clouds are seen rather low in the northern sky and may lose their characteristic blue colour through reddening by atmospheric absorption. As sunrise approaches, noctilucent clouds can appear in more and more of the sky. They are seen in the zenith quite often but with a low contrast because the Sun is then no more than 7°–8° below the horizon. Such occasions, though infrequent, are of particular interest because they offer the chance of seeing patterns in the cloud relatively undistorted by oblique viewing. Often there are several patches of billows in the cloud and the directions in which the billows run are not the same.

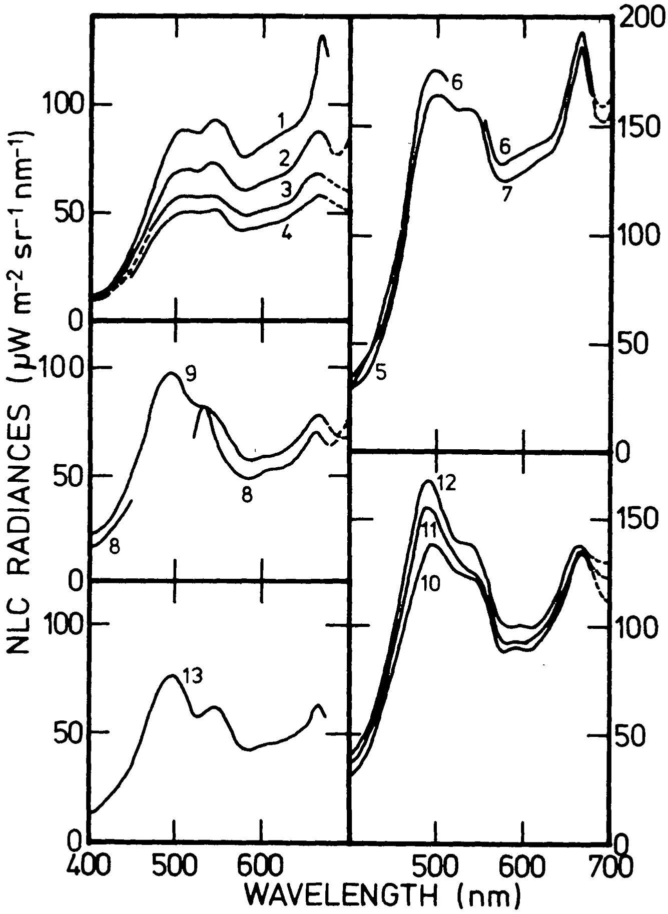

FIG. 2. Spectral radiance of noctilucent clouds observed from Aberdeen on 1974 July 23.


FIG. 1. Noctilucent cloud photographed from Aberdeen on 1972 June 26, 2400 UT.

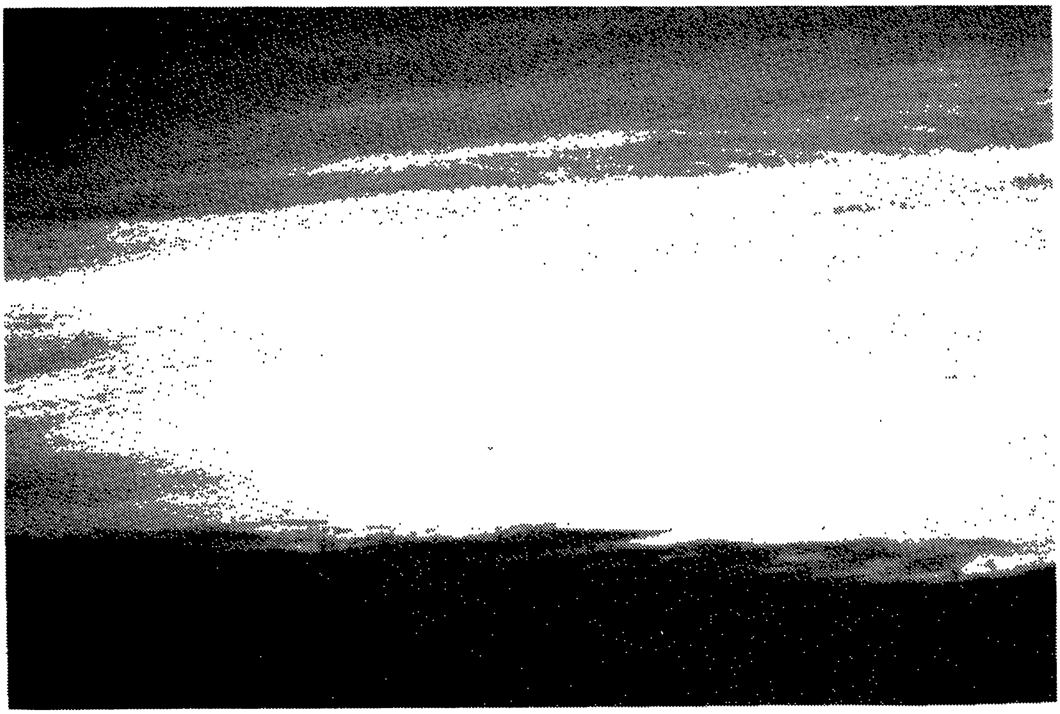
FIG. 11. Noctilucent cloud photographed from Aberdeen on 1975 July 5, 0058 UT.

[To face page 352

FIG. 12. Noctilucent cloud photographed from Saskatoon, Canada, by Oscar van Dongen.

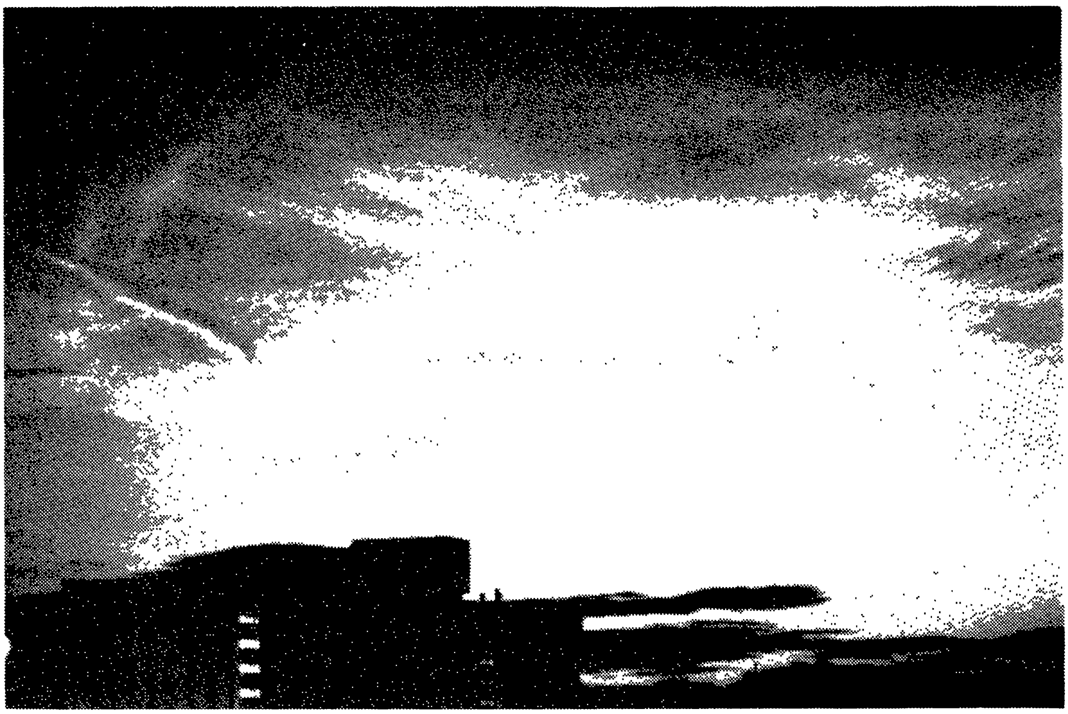

FIG. 13. Noctilucent cloud photographed from Aberdeen on 1974 July 12, 0102 UT.

Sometimes, two patterns seem to overlap and it is not clear at the present time whether such behaviour indicates *two* distinct layers of cloud or whether there are two groups of interpenetrating waves.

Noctilucent clouds are high in the atmosphere and remain visible throughout nautical twilight because they are still, at their great height, in direct sunlight. The blue colour of the clouds comes about through the effect of absorption by atmospheric ozone in the Chappuis bands, which are prominent in the yellow part of the spectrum (**6**). Fig. 2 shows plots of the spectral radiance of some noctilucent clouds observed from Aberdeen. They were low on the horizon (the elevation of the spectrophotometer field of view was set variously from 4·0° to 6·3°) and atmospheric absorption causes the blue:red ratio of radiance to be reduced markedly. The occurrence of a broad absorption centred in the yellow region is clear; the blue of noctilucent clouds comes *not* as a result of light being scattered from submicron particles but because the complementary colour is removed by absorption by stratospheric ozone. The sunlight shining on noctilucent clouds has passed obliquely through the ozone layer. As a result, a path length equivalent to several centimetres of ozone at atmospheric pressure is experienced by the light rays. The geometry of illumination of the clouds by the Sun is the well-known one of illumination by grazing rays, cut off below a height H_{sc} on the lower side by absorption in the troposphere (Fig. 3). There is, at any given solar depression below the horizon, an area of sky in which noctilucent clouds may be seen. It is a straightforward matter of geometry to calculate the extent of this area. Fig. 4 shows the sunward hemisphere of the twilight sky with the upper boundary of the illuminated area of cloud, assumed to be at a height of 82 km, calculated for three angles of solar depression below the horizon (9°, 12° and 15°).

The position in the sky of the edge of this area is changed little if the clouds are somewhat higher or lower than usual. There is also correspondingly little change if the obstruction provided by the troposphere, the magnitude of the screening height H_{sc} (Fig. 3), is greater or less than usual.

Observations over the last 100 years have shown that noctilucent clouds appear only in the summertime and only at mid- to high latitudes. They

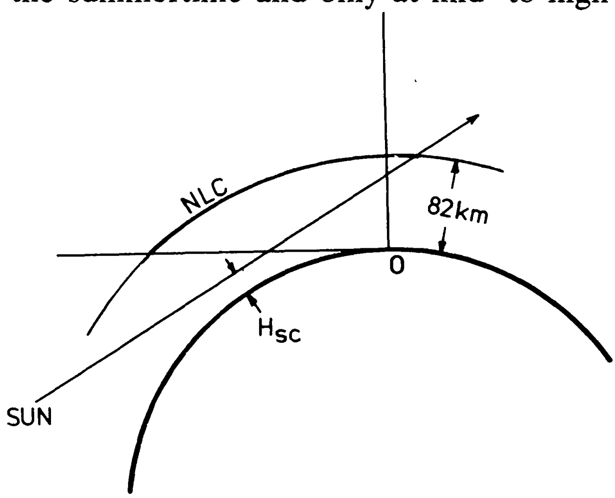

FIG. 3. The geometry of twilight illumination.

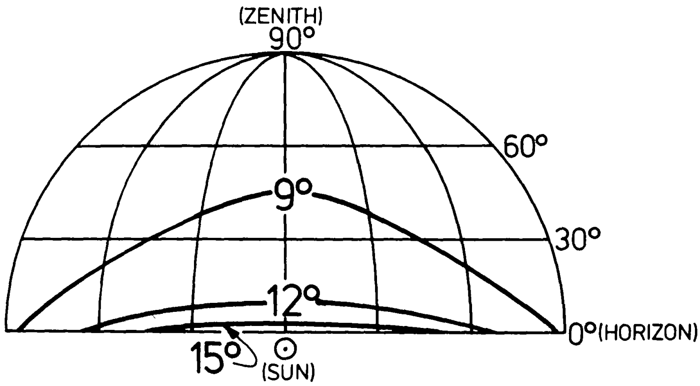

FIG. 4. The edge of the illuminated arch in the sunward hemisphere, calculated for three angles of solar depression angle.

have not been seen from ground level at polar latitudes because of daylight or bright twilight there during the summer; they are rarely, if ever, seen from latitudes less than about 45°. There are thus two *zones of visibility* and these are shown in Fig. 5. There are only differences in detail between the northern and the southern hemispheres; observation in the southern hemisphere is hampered by the filthier summer weather there and the relative absence of land (and population) in the observing zones.

The two auroral zones (stippled areas) are also shown in Fig. 5. Observations of noctilucent clouds made from Siberia may perhaps differ in kind from those made in Canada if, that is, the heating of the upper atmosphere by auroral particle precipitation is of significance in the climatology of the upper atmosphere. I know of no studies directly related to this although there is some evidence of difference in response to magnetic activity of noctilucent clouds seen from North America compared with those seen from north-west Europe. D'Angelo & Ungstrup (7) find that extensive noctilucent cloud displays over North America are seen only when the planetary magnetic activity index (K_p) is small, and has been low

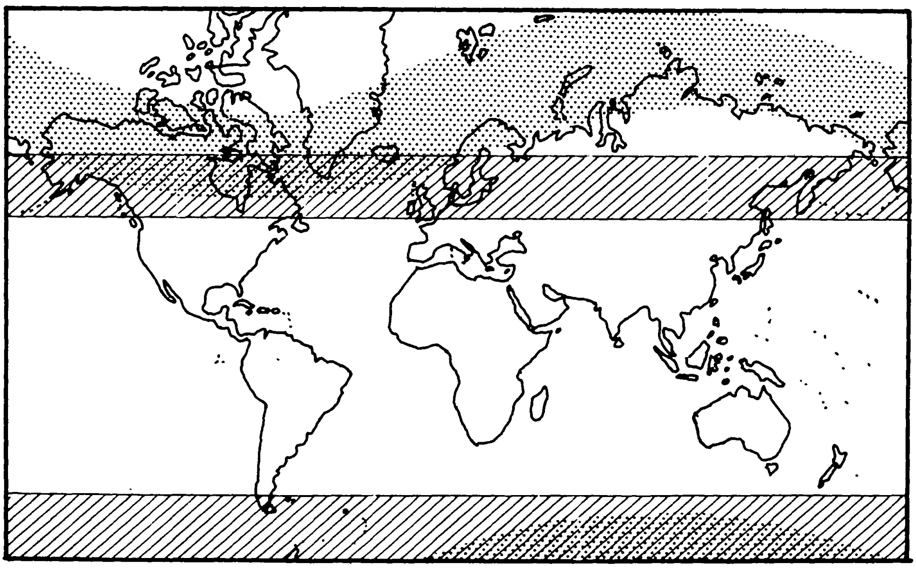

FIG. 5. Regions from which noctilucent clouds are most easily, and frequently, seen ('zones of visibility'). The positions of the two auroral ovals are indicated by the stippled areas.

for some time beforehand. This behaviour is not shown by similar observations from north-west Europe (**8**).

Satellites have extended the study of noctilucent clouds right to the pole in each hemisphere; visual observation by cosmonauts and astronauts and photometric detection of a scattering layer have both been reported. Cosmonauts in the *Salyut* spacecraft have photographed noctilucent clouds seen edge on, on the horizon. They appear in the pictures as a thin layer well separated from the underlying intense forward-scattering of the lower atmosphere. The clouds appear rather more developed as the spacecraft moves towards and over the noctilucent clouds.

The visual observations from space have on many occasions been related one-to-one with noctilucent cloud observations from the ground (**9**). The instrumental (photometric) observations are less immediately identified with noctilucent cloud. There are some observational difficulties. The *Solar Mesosphere Explorer* (*SME*) satellite orbits at local times of 3 am and 3 pm for the equatorial crossings. At these times, noctilucent clouds cannot be seen from ground level because of the brightness of the sky.

The satellite rolls in a cartwheel fashion, almost exactly in the plane of the orbit and can observe forward- and back-scattering from the same part of the atmosphere. The scattering layer appears clearly on a plot of photon counts versus tangent height of the direction of observation, here redrawn from (**10**) as Fig. 6. The photometers on the *SME* work in the ultraviolet, to take advantage of absorption by stratospheric ozone to give a dark background to the high scattering layers. In the absence of the absorption, the signal arising from Rayleigh scattering would rise exponentially in the lower part of this plot.

It is beginning to appear that the photometers are 'seeing' clouds made up of particles smaller than those in noctilucent clouds. Indeed, Olivero has said recently (**11**) that the *SME* photometers are 'almost blind' to noctilucent clouds. Why this should be so is not clear to me. The layer of cloud over the poles observed by the photometers on *SME* is now referred to as the Polar Mesospheric Cloud layer to avoid begging the question of its identity with noctilucent clouds as seen from ground level.

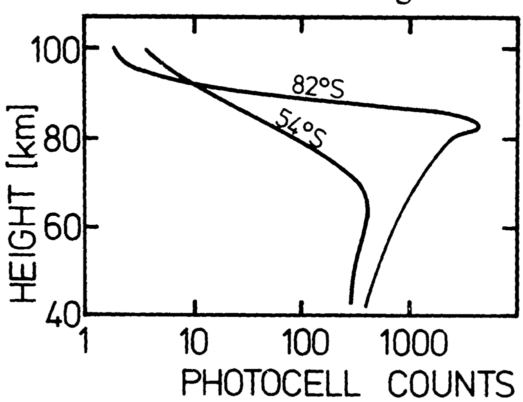

FIG. 6. Photometers on the *SME* satellite have shown the presence of a polar scattering layer; this example, redrawn from (**10**), shows a typical sample of the data. The photometer used a filter peaking at 0·265 μm. The curve labelled '82°S' shows the scattering layer; the curve labelled '54°S' is for reference to the atmosphere *without* a high-level scattering layer.

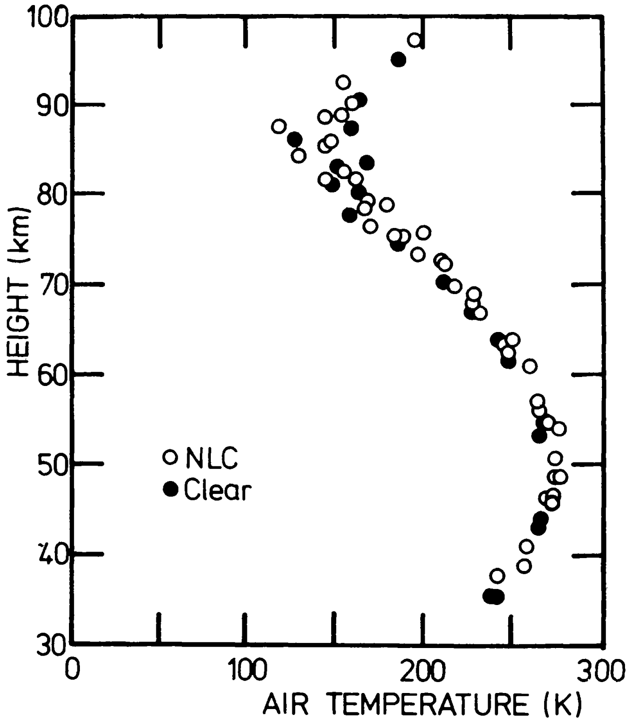

FIG. 7. Measurements made by rocket-borne thermometers of the variation of air temperature with height. Results from four flights are plotted, two of which were flights through noctilucent clouds.

PHYSICAL CHARACTERISTICS OF NOCTILUCENT CLOUDS

This, then, is the phenomenon: *quicquid nitet notandum*. From almost the very first, photographic triangulation showed that noctilucent clouds are situated at heights in the 80–90 km range. Their occurrence in the summer only suggests that a necessary condition for their nucleation and growth is the occurrence of exceedingly low temperatures in the upper atmosphere. These temperatures occur during the *summer* at heights of around 80–85 km and this is confirmed by rocket-borne measurements of temperature. Some quite typical measurements are shown in Fig. 7. It is clear from such data that these low temperatures are not a *sufficient* condition for nucleation and growth although they could be a sufficient condition for nucleation without subsequent growth of the embryonic particles. And indeed *vice versa*.

Fogle, working in Alaska, has assembled statistics (**12**) of the number of observations of noctilucent clouds reported in any one year. His data have been redrawn in Fig. 8. The data are subject to several disturbing factors as are most unsystematic visual observations. It has become clear from such data that there is no relationship between the occurrence of noctilucent clouds and the occurrence of the rare spectacular meteor showers or of volcanic eruptions. There *is* a relation between a low frequency of observation and the occurrence of widespread warfare but this has not been pursued as a topic in the *physics* of noctilucent clouds.

There is also a solar-cycle modulation of the frequency of occurrence of noctilucent clouds (**8**). The sense is antiphase and is presumed to be the result of increased mesopause temperatures at times of solar activity

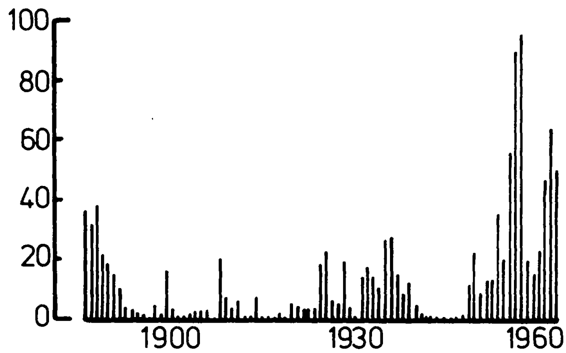

FIG. 8. The number of nights in each year (from 1885 to 1965) on which noctilucent clouds were reported to be present. The data are redrawn from (**12**).

leading to a decrease in growth rate or a decrease in the likelihood of nucleation.

The two candidates for a freezable constituent of noctilucent clouds are CO_2 and H_2O. Both are present in the upper atmosphere in trace amounts, a few hundred ppm for CO_2 and a few ppm for H_2O. The frost points for these are at less than 100 K for CO_2 and 140 K for H_2O at the pressures in the 80–90 km region. It is presumed, therefore, that noctilucent clouds consist of minute (water) ice crystals. This hypothesis has, in fact, borne up well and there seems to be no acceptable alternative. Collections made from rockets fired through noctilucent clouds show the presence of a volatile material in particles of sizes up to a few microns in diameter. The technique used is simply to expose trays as the rocket passes through a noctilucent cloud. The trays carry grids and films for electron microscopic examination subsequent to post-flight recovery of the trays. Sometimes a small solid nucleus is shown, often not. A most characteristic appearance is of a relatively-large (up to 1 μm or more in diameter) area on the collector that appears to have been the site of a droplet that has evaporated (**13, 14**). This disturbed area may, or may not, surround a small (less than 0·1 μm in diameter) nucleus which is opaque to electrons (**15**).

A typical particle density in a noctilucent cloud is $1\,cm^{-3}$. There are many times this number of ions (positive and negative) in the region as well as an appreciable amount of solid débris from meteor ablation (**16**), the so-called *meteor smoke*. Having an adequate number of nuclei in the region is not, therefore, a problem. The existence of an observable cloud is more a matter of sufficient aggregation of H_2O molecules on to nuclei rather than there being a sufficient number of nuclei present.

It is difficult to distinguish particles collected in noctilucent clouds from those arriving on the collecting surfaces from elsewhere (that is, contamination of the collection). The best technique involves *in-flight shadowing* of the surfaces (**17**). In this, two filaments are arranged, on opposite sides of the collecting surface, and one of them is used to evaporate an electron-opaque metal layer across the surface at the start of the sampling period. The second filament is used to shadow the surface at the end of the sampling period. Those particles which arrive on the collector between the times of the two shadowings show but one shadow. All others, those with two shadows (and, of course, those without a shadow) have arrived outside the sampling period.

BEHAVIOUR OF THE UPPER ATMOSPHERE

There are three principal ways to approach the study of noctilucent clouds. They may be observed and measured *per se*, to discover their nature, their constitution and the reasons for their existence at all in the upper atmosphere. This approach is basic, to be done to some extent before proceeding to the other two approaches. Having arrived at some (not necessarily complete) conclusions about the nature of noctilucent clouds, they might then be studied to give information about the climatology of the upper atmosphere, to give an extension to what is known about the general dynamical behaviour of air masses in the topmost part of the atmosphere regarded as a suitable study in meteorology. Noctilucent clouds can be used also as unique tracers of the behaviour of the upper atmosphere, in that they provide a visible layer which is bent and twisted by the passage of waves through the upper atmosphere, and which is moved bodily by the winds in the upper atmosphere.

(1) *The study of the formation of noctilucent clouds through study of the nature of the scatterers.* This is the *physico-chemical approach* which involves considering the chemical and ionic composition of the upper atmosphere together with analysis of the physics of growth of solid particles. By far the most comprehensive modelling of the growth of noctilucent cloud particles is that carried out by Turco and his associates (**13**).

Some simple (classic kinetic) ideas can be used to get a feel for the timescales that are involved in the physical processes of growth and evaporation. These times can, in turn, be used to evaluate proposed models in a general way.

The time taken to grow to a particular size of particle depends upon the amount of water vapour available in the region. Some calculations (**19**) based simply on the speed at which a cloud particle grows on a single ion (positively or negatively charged; it does not matter) give the figures listed in Table I.

The figures in column 3 of the table show the time in hours for the aggregation of a sphere of radius 0·1 μm given that the water vapour mixing ratio is as shown in the first column. Unless the mixing ratio in the upper atmosphere is much higher than is at present accepted, particles of the sizes that are observed in noctilucent clouds must take a day or two to grow.

If, for example, a wave propagating through the cloud causes a rise in temperature sufficient to lead to sublimation of the cloud particles, when

TABLE I

The calculated rates of change of radius of a spherical ice crystal aggregating H_2O molecules at an air temperature of 140 K and pressure of 5 μbar

Water vapour mixing ratio ($\times 10^{-6}$)	dr/dt (m s^{-1}) ($\times 10^{-12}$)	Time for growth (hr)
2	1·2	23
5	3·1	9
10	6·2	4·5

the temperature returns to its original (undisturbed) value, the cloud particles cannot be reformed on an equally short time-scale.

Haurwitz (**20**) has suggested that billows seen in noctilucent clouds may be the consequence of waves growing at an interface, probably a surface showing large wind shear. His analysis relies on growth times of the order of minutes, which were estimated in the first place by Hesstvedt who assumed a water-vapour mixing ratio of 1600 ppm – far too great for what is now known about the region. Similar objections rule out explanations using Scorer's model (for 'mackerel sky') of a row of vortices rather than of waves.

Wave forms seen as modulation of the thickness of the clouds are therefore more likely to arise from a redistribution of cloud particles than from sublimation and reaggregation processes.

Deposition of H_2O molecules on a growing particle occurs under the conditions of the Knudsen régime, in which the particle is smaller in size than the mean free path of molecules in the surrounding gas. The estimation of the fall-speed of a particle under these conditions, when the particle is non-spherical and where Brownian rotation is important, is not a trivial one (**21**).

(2) *The second approach to the study of noctilucent clouds is to use the clouds as a key to understanding the climatology of the upper atmosphere.* In this, the conditions involved in allowing noctilucent clouds to be seen at a particular time and place are considered.

It is well established that the low temperature at the summer mesopause is related to two things: the upper mesosphere is by and large transparent to sunlight and is not heated to any great extent by the Sun. The global circulation at these heights is from summer pole to winter pole and the air near the mesopause suffers considerable adiabatic cooling in the summer updraught.

Measurements using a falling-sphere accelerometer (**22**) to measure air density and thus infer air temperature have shown that the atmospheric temperature have been as low as 111 K at 93·6 km on one occasion. On this particular occasion, a noctilucent cloud was detected at a height of 83·5 km, where there was another temperature minimum, this time of 138 K.

A simple view, therefore, is that noctilucent clouds are nucleated over the poles (in the polar mesospheric cloud layer which does show small cloud particles). The embryonic particles are carried equatorward and upward by the general circulation of the atmosphere. In this airstream, the individual particles eventually grow to a size at which their fall-speed becomes sufficient to take them quickly out of the saturated airstream.

An ice crystal is able to evaporate at a much faster rate than it can grow because there is no longer a need to wait for a (comparatively infrequent) H_2O molecule to arrive and stick; in the conditions of low water vapour pressure that exist, as soon as the surrounding air becomes unsaturated, the ice crystal can evaporate at a speed dependent principally only upon its temperature. In the simplest case, this temperature might be assumed to be

Table II

Maximum possible rate of evaporation of a spherical ice crystal

Crystal Temperature (K)	dr/dt ($m\ s^{-1}$)	Time for disappearance
130	$2{\cdot}2\times10^{-14}$	52 d
150	$1{\cdot}1\times10^{-11}$	160 m
170	$1{\cdot}2\times10^{-9}$	85 s
190	$4{\cdot}7\times10^{-8}$	2 s

that of the surrounding air, in which case a straightforward calculation (19) of the rate of evaporation can be made. The rate of decrease in radius of the crystal (assumed to be spherical) does not depend on the radius of the crystal and is a quickly-varying function of temperature, as indicated in Table II.

A noctilucent cloud is seen only when it is in sunlight and the polar scattering layer spends much of its time in sunlight. In addition, the clouds lie just above the Earth and its lower atmosphere. Both are strong emitters of infrared radiation and ice has strong absorption bands in the infrared. It follows that there is an interesting problem in radiation transfer here; Baibulatov & Ivaniya (23) have made estimates of the increase in temperature over that of the surrounding air. For radii up to 0·1 μm, the particle temperature is very close to ambient. For larger particles, there may be a temperature excess of up to 10 K but little likelihood of more than this.

Remember that immediately below the cloud layer, if it is at or near the mesopause, the air temperature around the particle increases rapidly as the particle falls. In consequence, one expects a cloud layer that is sharply defined on the lower side. This is, in fact, what is always seen. Furthermore, it is inevitable that a cloud will grow and settle to lie with its base just below the mesopause. Noctilucent clouds must be visible sheets marking the position of the saturation level. This will be almost a constant temperature surface (irrespective of changes in the local water vapour mixing ratio) because the saturation vapour pressure of H_2O over ice is a very sensitive function of temperature at these low temperatures.

The saturation of air at these heights is set principally by the temperature rather than by the water vapour content. Fig. 9 shows plots of some rocket measurements of the temperatures near the mesopause on two occasions, one when noctilucent clouds were present, one when they were not. Superimposed on the plot are three dashed lines giving the frost point (and its change with height) for three water vapour mixing ratios. The saturation vapour pressures over ice at these exceedingly low temperatures were calculated using the Clausius–Clapeyron relation to extend measured values down by some 100 K.

It seems reasonable, therefore, to assert that noctilucent clouds seen at high mid-latitudes consist of particles close to the end of their lives when they are at their biggest and brightest, just before they fall to sublimation.

Some support for this simple view has been provided by rocket-borne chaff measurements (25) of wind speeds above the mesopause. These are summarized in Table III.

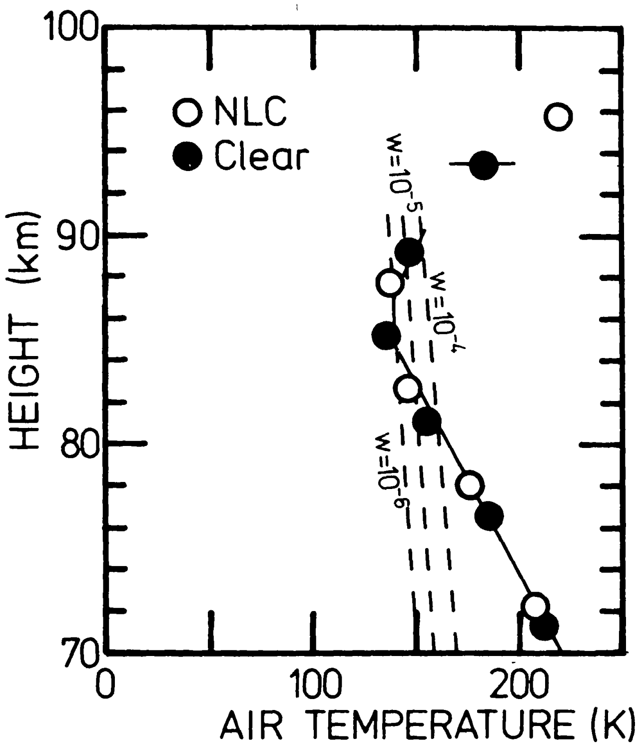

FIG. 9. More measurements of air temperature made by rocket-borne thermometers in the presence of, and in the absence of, noctilucent clouds. The dashed lines superimposed on the plot show the frost point, and its change with height, for three water vapour mixing ratios.

TABLE III

Wind speeds above the mesopause (25)
(the average of speeds at all heights to rocket apogee)

Noctilucent clouds absent ($m\ s^{-1}$)	Noctilucent clouds present ($m\ s^{-1}$)
90	37
95	17
95	60
	45
	[35]

It seems clear from these data that noctilucent clouds are associated with the occurrence of *low* wind speeds just above the mesopause. (The final figure in the right column is placed in brackets because on this occasion the rocket did not penetrate the mesopause and this wind speed is what was measured right at the mesopause, at the apogee of the rocket.) The occurrence of *low* wind speeds is deemed to be necessary because time is needed for the cloud particles to grow to observable sizes.

A more detailed analysis involving the comparison of meteor-trail drifts with the occurrence of noctilucent clouds throws doubt on this view. Muller (26) has made a very large number of measurements of wind speeds in the upper mesosphere and lower thermosphere from Sheffield (27) and elsewhere in the United Kingdom. He has placed a meteor radar at a field site just north of Aberdeen. When the radars are operated at the same time from both Sheffield and Aberdeen, two volumes of the upper atmosphere are observed simultaneously from directions at right angles. Radial components are measured at Sheffield and Aberdeen and thus give unambiguous measurements of the wind *velocity* in the two atmospheric volumes at heights between 70 and 110 km.

Data have been plotted (Fig. 10) for a week in 1982 July when there was considerable noctilucent cloud activity on three nights. Inspection of the results shows that one can make *no* assertion that the winds in the upper atmosphere change when there is a noctilucent cloud from when there are no, or very weak, noctilucent clouds. The convention used to specify the direction of the wind vector is the mathematical one: 0° is a wind blowing towards the east, 90° towards the north, and so on. (Meteorologists on the one hand and aeronomers on the other disagree profoundly on how to refer to wind direction: the former refer to the direction *from which* the wind comes, the latter to the direction *to which* the wind is blowing.)

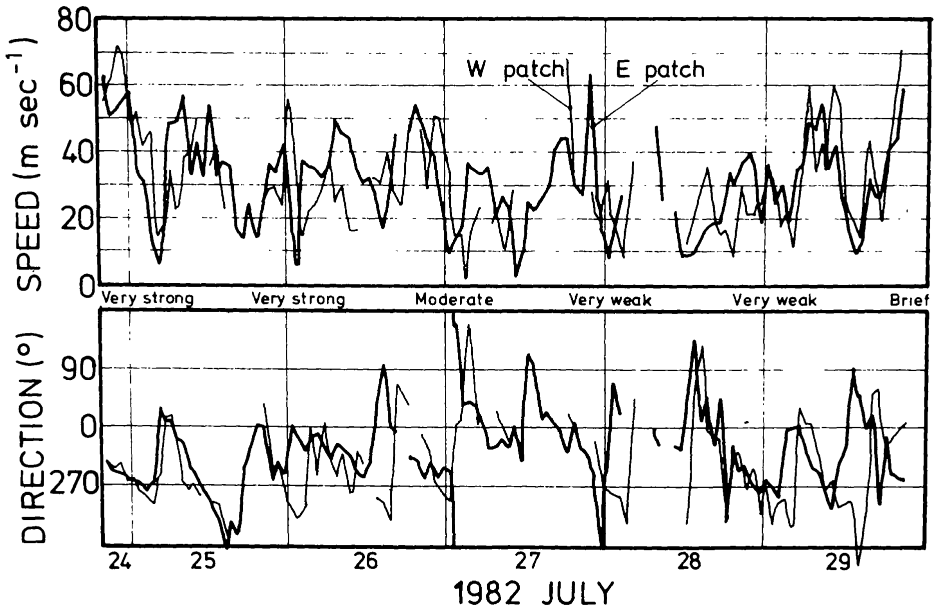

FIG. 10. Wind speeds and directions measured from Sheffield and Aberdeen in 1982 July. The data are for two separate volumes of the atmosphere ('east patch' in bold line; 'west patch' in faint line) separated by 7·5°; in longitude. A summary of the appearance of noctilucent clouds during the six nights is given along the centre line.

The Sheffield/Aberdeen data have shown also that the 'background' wind (i.e. the steady component that remains after removal of tidal oscillations) shows a significant alteration in direction when the east and the west volumes are compared. These changes in direction have been interpreted as showing geostrophic winds flowing round cyclones and anticyclones in the upper atmosphere. It seems probable that the meteorology of the upper atmosphere, involving warm fronts and cold fronts, will need to be invoked in explaining the occurrence of noctilucent clouds. At present, there are no weather maps available for the 1 and 10 microbar levels.

(3) *Lastly, noctilucent clouds may be used as tracers of atmospheric movement to study air flow, turbulence and wave motions at the height of the*

cloud display. Not a great deal has been done on this other than the taxonomy (**28**). In the photograph reproduced in Fig. 11, there are *billows* and *bands*. Bands are the long stripes lying across the sky, and billows are the more localized patches showing shorter wavelengths lying on top of the bands. Haurwitz & Fogle (**29**) have made a survey of measurements and conclude that, as general rules, bands have wavelengths of 10–75 km and amplitudes between 1·5 and 3 km while billows have wavelengths of 3–10 km and amplitudes between 500 and 1500 m. Bands have been seen to last for several hours while usually billows have lifetimes of a few tens of minutes only. It has been suggested that the billows (sometimes called ripples) are the breaking of the waves causing the bands.

There are many examples of billows appearing almost in isolation. Billows are visible even when noctilucent clouds are near the zenith and are thus evidence of a real variation in particle numbers. They cannot be simply just the effect of obliquely viewing a rumpled, optically-thin, layer. With the amplitudes and wavelengths that are found to be typical of such clouds, horizontal divergence in the wave motion (**30**) is more than sufficient to account for the variation in numbers of particles. Condensation and sublimation need *not* be invoked.

There is some evidence that the occurrence of billows is related to noctilucent clouds forming in any part of the atmosphere that lies in the lee of a major mountain chain. The photograph reproduced in Fig. 12 was taken some years ago in Saskatoon. It shows ripples filling the illuminated area of clouds. From Scotland, this is a rare form, not seen in the last 15 years. Does this point up the difference between the geographic positions of Saskatoon, to the east of the Rockies, and of Aberdeen, east of the Atlantic? Do the noctilucent clouds seen from Saskatoon often lie in a lee-wave system of ripples?

George Witt, in Stockholm (**31**), has been very successful in taking photogrammetric pairs of noctilucent clouds. He used high-quality stereo cameras at observing points 51·5 km apart and was able to use stereophotogrammetric plotting in his analysis of the photographs. Noctilucent cloud structure is frequently perceived as the result of obliquely viewing an optically-thin layer (an optical thickness of 10^{-4}–10^{-5} in the vertical is normal) which has waves in it. To some extent, therefore, what you see may change when you change your viewpoint and some of this effect can be seen in these two photographs. Nevertheless, there is much similarity in Witt's pictures taken from widely separated places and stereofusion is possible in a very satisfactory way.

The analysis showed that the cloud was in the form of a practically continuous layer exhibiting a more or less regular pattern of deformation from the horizontal. The speeds of horizontal flow could not be estimated with any certainty. Observation of the movement of some bright patches that were seen early in the display gave wind speeds of 80–120 m s^{-1} and, using this speed, the waves in the clouds were found to be moving at 70–135 m s^{-1} in the frame of reference of the cloud layer.

The amplitude of the waves can be 2–3 km, a large fraction of the atmospheric scale height. That is to say, the pressure of the atmosphere at the bottom of the wave is appreciably greater than that at the top of the wave. The waves are not small perturbations of the undisturbed atmosphere: they show non-linearity.

There is a tendency to group all the waves as *internal gravity waves*, with energy propagation upwards from sources in the troposphere (e.g. waves generated in air flow over mountain ranges or in thunderstorms). Noctilucent clouds often show a localized organization of the waves into packets, perhaps tens of kilometres across, and this throws doubt on suggestions involving unfocused sources many tens of kilometres away from the cloud layer. Little consideration has been given to explanations *not* involving internal gravity waves.

The photograph reproduced in Fig. 13 shows what looks like a single wave in the noctilucent cloud layer. In an optically thin layer, bright areas result from tilting of the layer to bring it lying more *along* the line of sight. Tilts of the opposite sign bring the layer more perpendicular to the line of sight and result in a dark band. Thus the bright stripe and dark band seen in the photograph result from a single *trough* in the cloud layer. The conditions at the mesopause are right for the propagation of single waves: non-linearity is present and the dispersion is normal (the longer wavelengths travel more quickly than do shorter wavelengths). Whether these single waves are *solitons* remains to be seen. I *do* have pictures of what appear to be single waves crossing each other and emerging with their identities intact but I cannot *prove* that the waves are not in separate layers.

Analysis of the waves occurring in a region where the atmosphere is neither isothermal nor stationary is complicated. Haurwitz (**20**) has made studies which go into the most detail so far. Just below the mesopause, the lapse rate of the atmosphere has been found to be, at times, one-half the adiabatic lapse rate. The Brunt–Väisälä frequency will, at these times, be one-half what is expected for an isothermal atmosphere. It follows from this that some upwardly propagating internal gravity waves will become evanescent at the mesopause. However, the vertical extent over which evanescence may occur is likely to be only one or two kilometres in depth, rather less than the wavelength of the waves. In this case, one probably has the internal gravity wave equivalent of the frustrated total internal reflection that is found in optics.

CONCLUDING REMARKS

It may be of interest to give details of photography of noctilucent clouds. The pictures taken from Aberdeen and reproduced here were all taken on Kodak Ektachrome (ASA 200) colour film. The camera is 6×6 cm format with an *f*/2·8 lens. The exposure used can vary between 20 s, used at times close to midnight late in July, to 4 s when photographing close to civil twilight.

A suitable repetition rate for timelapse photography is for one exposure every 3 or 6 s; with an *f*/1·4 lens, the exposure time fills the interval between exposures, that is to say, it is either 2·9 or 5·9 s. The film used is Kodak VNF 7239 16-mm colour film which has a rated speed of 160 ASA.

Experience shows that satisfactory television pictures may be got with an ordinary silicon (not intensified) cathode and a lens with an aperture of *f*/2·8 or *f*/4. I have obtained over the last few years several hours of recordings of the detail and development of wave structures in noctilucent clouds. However, the most satisfactory pictures of detail are obtained with a 35-mm camera with a 50-mm lens and an aperture of *f*/2·8 using Ektachrome (400 ASA) film. The camera is placed at the exit pupil of a guider which has a 50-mm OG and an eyepiece of magnification ×7. The film is force-developed in the first developer to give a fourfold increase in speed.

Finally, there is a curious absence of historically early observations of noctilucent clouds (**32**). They were first noted in 1884 (**1**) and no earlier mention of them has been identified. It is of interest to note that Lewis Carroll (**33**) has the Walrus and the Carpenter recite to the baby oysters lines which sound very like a description of noctilucent clouds:

'The Sun was shining on the sea,
Shining with all his might.
He did his very best to make
The billows smooth and bright –
And this was odd, because it was
The middle of the night.'

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