Can I see noctilucent clouds?

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This question was recently asked by an observer in Inverness (latitude 57.5°N) which is one of the best places from which to see noctilucent clouds (NLC). The study of NLC is at the present time exciting a lot of interest among upper atmosphere physicists because the physics of occurrence of the clouds is not well-known. In addition, it may be that 'global warming' is showing clearly in the frequency at which NLC are seen. The Association's Aurora Section is currently the custodian and generator of the longest series of visual observations that is available for research. Whether a noctilucent cloud is seen depends on several factors: the observer's position, the season of the year, the time in twilight, refraction, and absorption of light from the setting Sun. These are discussed in this paper.

Introduction

At latitudes above 50°, the summer nights are quite light; at the solstice civil twilight lasts all night for latitudes between 60.6 and 66.0°. The conditions are not good for astronomical observations but can be excellent for twilight exploration of the upper atmosphere.

At high latitudes and heights around 80–90km, the atmosphere is very cold during the summer; paradoxically, this part of the upper atmosphere is coldest in summer and warmest in winter. Although the upper atmosphere is known to be dry, with a water vapour pressure amounting to just a few millionths of the local air pressure, **clouds** are seen there. These clouds shine in the summer twilight sky with a pale blue colour and their occurrence, shapes, and position in the sky have been observed and noted for over one hundred years (the first published note was by Leslie[1] in 1884).

Paton,[2] then head of the BAA's Aurora and Zodiacal Light Section, began annual reports in 1964. The Association now possesses an unbroken series of observations which have been listed in some detail in the *Meteorological Magazine*[3] until 1985. Shorter annual reports are now being published; at first they continued to appear in the *Meteorological Magazine* but now appear here in the *Journal*. Gavine's most recent summary of noctilucent cloud observations[4] includes a pair of very beautiful colour pictures taken by Holger Andersen in Denmark. Original reports and photographs from recent years are stored in the Archives and Special Collections of Aberdeen University (MS3152/24/) where they are freely available for examination.

Latitude variation

Because of the extremely low water vapour pressure in the 80–90km region of the atmosphere, it is clear that nucleation of clouds cannot occur there unless the air temperature is very low. Extremely low temperatures (sometimes below 110K, –163°C) have been measured in rocket soundings over northern Norway during summer months.

The ice crystals in the clouds begin to grow on nuclei, which may be ions or meteoric smoke particles, only at the very lowest temperatures which are encountered at around 90km height. During the summer, the winds at these heights flow out from the pole and the geostrophic wind direction is, therefore, generally towards the southwest. The ice crystals take many hours to develop into an observable cloud and during this time the clouds are swept many hundreds of kilometres out from and around the pole.

Observations from satellites disclose that there is a semi-permanent cloud layer surrounding the summertime pole and noctilucent clouds form the outer parts of this cloud. As the cloud particles grow in size, they fall at an ever-increasing speed until eventually they drop into a region of the atmosphere where the air temperature is high enough for the air to be unsaturated. The particles then begin to evaporate and lose mass; their fall speed decreases, resulting in an abrupt disappearance of the cloud. NLC appear in a horizontal layer at an air temperature which seems to be always close to 150K (–123°C), according to the rocket soundings of Lübken, Fricke and Langer.[5] The visual observations suggest the final stage in the life of a noctilucent cloud is reached at latitudes around 55–65°. It would be interesting to know if the latitude of this edge has decreased in the past thirty years and if it is decreasing at the present time.

Seasonal variation

The 32 years of data show that the clouds occur principally within a month of the solstice. They are most likely to be seen on the night of July 3/4; the earlier decile (90% of the sightings occur after this date) is June 5/6 and the later decile (90% of sightings earlier) is July 31/August 1. Space-borne photometers have shown that the seasonal variation is a true summer maximum, for in the southern hemisphere the clouds are most frequently seen in early January. The data have also shown that the frequency of occurrence of the clouds, that is to say the total number of nights on which the clouds are seen in any one year, has been rising over the last three decades and they are now twice as likely to be seen as they were in the 1960s. The reason for this change has been discussed in a number of papers.[6,7] The year-to-year numbers also show an obvious 10.5 year variation[8] which could be the effect of solar activity on the temperature of the upper atmosphere. Also, the numbers of observations in 1992 and 1993 were obviously low and this is probably the effect on the upper atmosphere of the volcanic eruption of Mount Pinatubo in July 1991. Satellite observations[9]

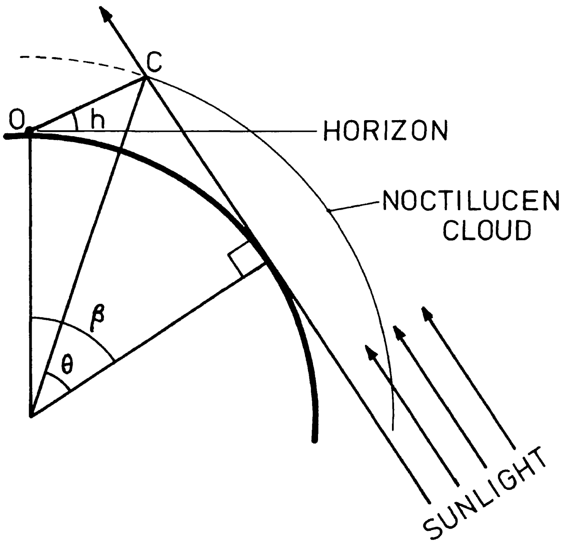

Figure 1a. The simplest geometry of viewing a noctilucent cloud. The observer O, essentially at zero height above the Earth's surface, will see an NLC lit from the horizon up to the point C where sunlight that grazes the Earth's surface passes through the cloud.

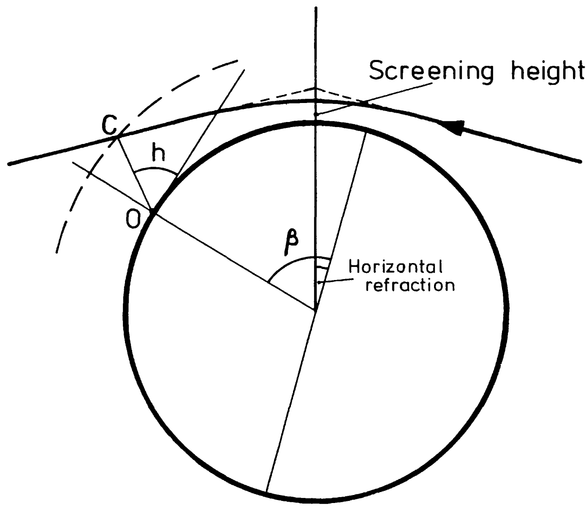

Figure 1b. The passage of the grazing ray. It will penetrate only to a minimum height, the 'screening height', and will be affected by atmospheric refraction.

have shown that this particular eruption had a very evident effect on the temperature of the stratosphere at about 28km height although curiously not at 54km. The relationship between noctilucent clouds (in the mesosphere) and conditions in the stratosphere is currently not known, but that there is a relationship is becoming more and more strongly suspected.

Observing NLC

There are four conditions that must exist if an observer is to see a noctilucent cloud:

1 The cloud must be over the observer's horizon. Because the clouds are always close to a height of 82km,[10] the clouds must be within approximately 9°.7 of the observer's position. Almost always, the clouds first appear poleward of the observer so the cloud's latitude must be within 9°.7 of the observer's. Experience shows that the clouds are a polar phenomenon and the outer edge appears frequently to be close to 60°; therefore, it is best to attempt to observe them from a latitude higher than 50°.

2 It must be the season for the clouds to appear and, in northern Europe, this means starting to look for the clouds in mid-May and giving up after mid-August. But (and this is a big but) it could be that NLC appear well out of season. There has been an authentic observation of NLC from the British Antarctic Survey station Faraday (65° south latitude) in June;[11] as a physicist has remarked, 'I wonder just what the conditions were in the mesosphere at that time'.

3 The sky must be dark enough for the sunlit clouds to be seen behind the foreground of the twilight sky. The statistics show that, except in rare cases, this means that the Sun must be at least 4° below the horizon. In the years 1964–1995, NLC were seen on 1013 nights. The angle of the Sun below the horizon, the 'solar depression angle', β, was calculated for the time and place of the earliest and of the latest observations on each night. The decile of the earliest observations is β= 5°.4 and for the latest observations β= 5°.3. There is, therefore, an upper limit on the latitude for observing NLC. If, at the summer solstice, you try to see the clouds from a latitude greater than 61°.2, you have a 90% chance of not seeing them because the sky is too bright even at midnight.

4 The observer's sky must be clear!

Where in the sky

When there is a noctilucent cloud in the observer's sky and all the conditions are satisfied, the extent of the visible cloud will be limited by the geometry of viewing (see Figure 1a). The cloud must be sunlit and therefore it will appear somewhere within the 'twilight arch' which is the area of the sky in the direction of the Sun in which an NLC is able to be illuminated. The arch is centred on the azimuth of the Sun and symmetrically on each side of this azimuth. At the horizon, the width of the twilight arch is greatest and the arch extends up into the sky to some maximum angle of elevation, h. With no allowance for atmospheric refraction or absorption, i.e. with the solar grazing ray being simply the tangent to the Earth's surface, this maximum angle of elevation is given by

$$\cos h = \sin(\beta - \theta) / \sqrt{[1 + \cos^2\theta - 2\cos\theta \cos(\beta - \theta)]}$$

in which $\cos\theta = R/(R+H)$. The radius of the Earth is written R (6362km) and H is the height of the NLC (82.5km). This first calculation shows that when β is 15° or more, the NLC will be within 5° of the poleward horizon. When β is 3° or less, the NLC can be sunlit when within 5° of the equatorward horizon, that is, the cloud may be seen more or less anywhere in the sky. (This does happen on occasion.) The top of the twilight arch is at the zenith when β is 9°.2.

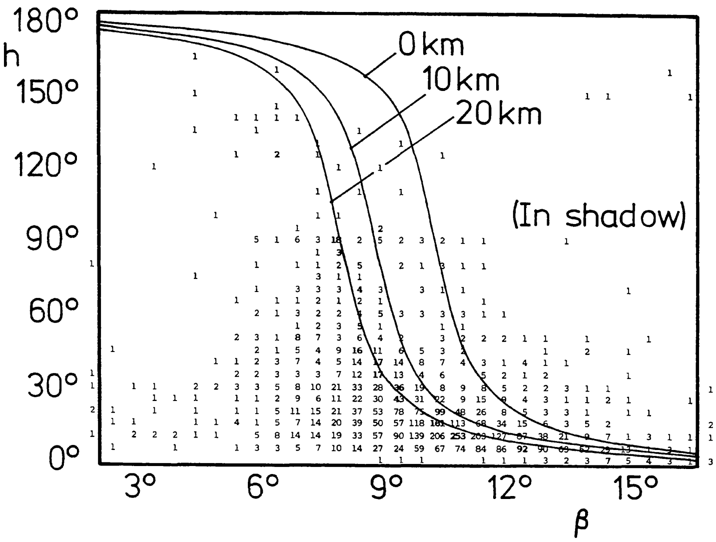

Figure 2. A listing of the numbers of observations that fall into the set of h, β boxes. Calculated lines for three screening heights are superimposed on the array of boxes.

Screening height

Atmospheric refraction is important and absorption in the lower atmosphere affects the height at which the lowest effective ray of sunlight passes over the terminator. Figure 1b indicates how a ray of sunlight will pass through the lower atmosphere on its way to the NLC. Tracing this ray with precision demands a small-step integration of the equation of refraction in the atmosphere.[12] Study of the result of such an integration shows that for NLC a simpler picture is sufficiently accurate and more than adequate. The limiting ray can be regarded as being made up of two asymptotic rays meeting above the terminator at an angle equal to 180° minus twice the horizontal refraction that occurs at the level of the minimum height, or the 'screening height', of the real ray.

The actual screening height on any given night is unknown but a typical value can be estimated by plotting the detailed observations contained in the archive of NLC. Observers have been asked to measure the right-hand edge of the display and the left-hand edge and to measure the highest point. On occasion, of course, the limits are set by what the observer can see through tropospheric cloud; on occasion, too, the upper edge of the display is a true boundary of the equatorward extent of the NLC. While keeping these points in mind, nevertheless the solar depression angle at the observer has been calculated for all of the reported cloud extents and the 4350 separate observations are plotted with elevation angle of the highest point in Figure 2.

The numbers shown in Figure 2 are formed as follows: each observation consists of the latitude and longitude of the observer, the time (UT) of the observation, the azimuth of the left-hand side of the noctilucent cloud, the azimuth of the right-hand side of the cloud, and the elevation angle of the highest point of the cloud, h. (When the cloud extends past the zenith, h is taken to be 180° minus the elevation angle.) These numbers are used to calculate the zenith angle (90+β) of the Sun. The values of β are grouped into half-degree-wide classes and the values of h into five-degree-wide classes. A particular observation thus contributes **one** to the total in the appropriate (β, h) box on the diagram.

The boxes plotted in Figure 2 extend from β= 2.5 to β= 16°.5. The thirteen numbers shown outside the plotted area are for observations with β beyond this range. Each of these observations has been checked and there is nothing obviously wrong with any of them; it could be that the observer has wrongly reported the time of the observation, it could be that they are true and correct observations of unusual NLC. The three lines ('0km', '10km', and '20km') are the lines calculated as described above for three screening heights. The horizontal refractions are 0.59, 0.14 and 0.035° respectively. Note that β is calculated for the centre of the Sun's disk so that there will be some illumination extending for one-quarter of a degree (half a box) along the β axis to the right of each line. Filled boxes to the right of the 0km line refer to observations for which a cloud at 82.5km height cannot be sunlit in normal conditions. **Abnormal** conditions might include clouds at a height greater than 82.5km in the atmosphere, anomalous atmospheric refraction, incorrect identification of a tropospheric cloud as a noctilucent cloud, and perhaps observation of a moonlit NLC in a dark sky. The number of such observations is 1.8% of the total.

Observer error in measuring or estimating the angle h will contribute a little to the scatter of points in Figure 2. Simmons & McIntosh[13] show that there is a difficulty in estimating elevation angle as h rises towards 90° (overhead observations). If the marginal totals for h are plotted (Figure 3) it is clear that for h above 20°, observers tend to report values that are rounded up or down to a multiple of ten degrees. This is a well-known phenomenon in statistics; some numbers are 'popular'.

In each horizontal line of numbers (constant h), the statistically most-likely β is printed in bold figures. Inspection

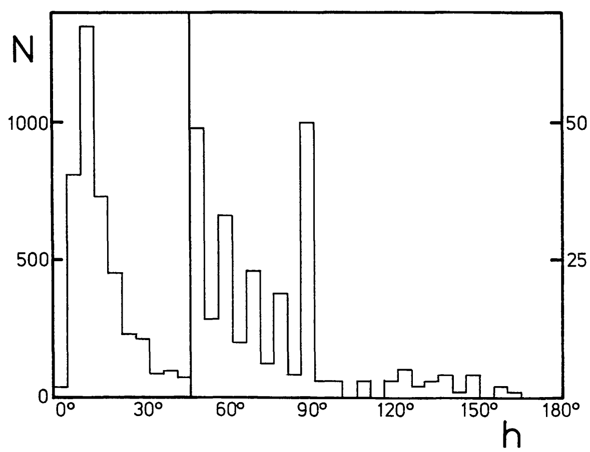

Figure 3. A histogram of the marginal totals from Figure 2. Note that the right-hand side of the plot (h>45°) is plotted at twenty times the scale of the left-hand side.

shows that these cluster around the line for a screening height equal to 20km. It seems justifiable, therefore, to assert that under normal conditions the screening height is 20km. This statement does not imply that an estimate of screening height that is not close to 20km is wrong. Taylor, Hapgood & Simmons[14] give the results of measurements of h on the night of 1979 July 10/11 and these, when plotted on the (β, h) graph, fall just one quarter of a degree to the right of the 10km curve, in fair agreement with their conclusion of 7km for the screening height on this occasion. In an earlier paper, Simmons[15] gives a list of the maximum elevation of the NLC he measured on the night of 1976 June 18/19; his data, plotted on the (β, h) graph lie on a line just one-quarter of a degree to the right of the 20km line. Although he adopts a screening height of 30km in calculating the height of the NLC, it would seem that a rather lower screening height would have been more appropriate. (Both these sets of measurements were for β lying in the range 9.9 – 11°.7 and h between 13.0 and 18°.0.)

Concluding remarks

The calculations refer only to whether noctilucent clouds can be sunlit. To calculate the luminance, or better the radiance, of an NLC calls for calculating the actual raypaths of sunlight through the lower atmosphere for assessment of the optical absorption that occurs. Avaste, Gadsden and Grechko[16] present these calculations and find that, in addition to reddening resulting from atmospheric scattering, the shadow of the atmospheric ozone layer is quite obvious and it causes the characteristic blue colour seen in NLC. Ostdiek and Thomas[17] have published similar calculations and extended them to include the effect of scattering by small ice crystals in the cloud. They thus calculate the radiance and the colour of NLC for comparison with observation.

It is worth pointing out that a noctilucent cloud layer provides a reflecting screen upon which the shadow of the Earth is projected. On occasion,[16] the upper edge of a noctilucent cloud is deep red just as, on occasion, the Moon in eclipse shows an intense red colour. NLC provide a more frequent monitor of the Earth's shadow than is provided by the eclipsed Moon. The detailed analysis of solar spectral irradiance that has been developed for studying NLC can be extended without difficulty to discuss the appearance of the Moon in eclipse.

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