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Noctilucent cloud observed in late April at South Pole Station: Temperature anomaly or meteoritic debris?

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Abstract. A sunlit cloud was observed near the horizon at South Pole Station (90°S), four months after summer solstice in 1992, at a solar depression angle of 14.6°. The angular location of the transition from sunlit to twilit cloud in the photograph establishes the cloud height at about 80 km. The cloud extended horizontally at least from 81° to 85°S and from 40°W to 20°E. The probable origin of this cloud by formation of water-ice crystals near the mesopause suggests that mesospheric temperatures occasionally deviate by at least 70 K from their climatological means. An alternative explanation that the cloud was a debris cloud formed by disintegration of a reentering man-made satellite is ruled out. A debris cloud from an entering meteoroid is a possible explanation but would be unprecedented. Hydroxyl airglow emissions at the south pole in May give a frequency of 1% for mesopause temperatures below 155 K, consistent with the rarity of out-of-season sightings of noctilucent clouds in Antarctica.

Introduction

Noctilucent clouds (NLCs) occur in the upper mesosphere at high latitudes, mainly in the three months surrounding summer solstice, and can be observed visually only at night. These constraints put the most favorable viewing location in the latitude zone 50°-65°, which in the southern hemisphere is mostly ocean. Noctilucent clouds are therefore rarely observed in the southern hemisphere [*Fogle and Haurwitz*, 1966]. At the south pole the Sun sets on the March equinox, long after the end of the NLC season.

A few out-of-season NLCs have been reported in the Antarctic [*Kreem*, 1967, 1968; *Kilfoyle*, 1968; *Dolgin and Voskresenskiy*, 1973]. Some of them were unlikely to have been true NLCs, as discussed by *Gadsden* [1982] and *Gadsden and Schröder* [1989], and some others lacked adequate documentation. However, a report of NLCs on two occasions in June 1985, from Faraday Station at 65°S on the Antarctic peninsula [*Griffiths and Shanklin*, 1987], although disputed by *Schröder* [1988], was subsequently documented by a photograph [*Shanklin*, 1988] and judged by *Gadsden and Schröder* [1989] to be a true NLC. In spite of its good documentation, the sighting does not seem to have inspired a search for its cause. In this paper we describe another out-of-season NLC, with some discussion of the circumstances that may have caused it.

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Observation

On April 29, 1992, a sunlit cloud was observed at South Pole Station, near the horizon in the direction of the Sun, from approximately 1100 to 1300 UT (2300-0100 LT). The sunlit portion of the cloud moved west with the Sun during the 2-hour event. Seven of the station personnel observed the event, and two cameras photographed it (Figure 1). No other similar event was observed during the entire 6-month night of 1992.

Parts of the cloud in Figure 1 are hidden by dark tropospheric clouds in the foreground. The cloud appears to continue upward above the part illuminated by direct sunlight. It is unclear how high this twilight-illuminated cloud extends. The horizon line is tilted in the photograph because the camera was not leveled.

The camera's lens had a variable focal length (70-210 mm, f/4). The focal length and exposure time were not recorded. However, several stars are apparent, and they allow accurate scaling of all angles in the photograph. At the south pole the horizon always coincides with the celestial equator. The stars in Figure 1 belong to the constellations Cetus and Eridanus; they have been identified by reference to the Cambridge Star Atlas [*Tirion*, 1991, chart 8]. They are indicated in Figure 2, an interpretation of the photograph. The bright star in the top left is Deneb Kaitos (β-Ceti, declination 18°S, magnitude 1). The less bright star at the extreme right is Zaurak (γ-Eridani, declination 13.5°S, magnitude 2). The length of the star streaks is 1.8°, indicating a 7-min exposure.

The cloud does not exhibit the characteristic striated appearance of typical NLCs [*Fritts et al.*, 1993]. This could be due to the blurring effect of the time exposure as well as to the extreme obliqueness of the near-limb viewing.

Cloud Height, Dimensions, and Lifetime

The sunlit part of the cloud in the photograph extends from about longitude 20°E to beyond 40°W (scale on top axis of Figure 2) and from the horizon to 2°-3° elevation. The boundary between sunlight and twilight on a cloud at height

Figure 1. Photograph taken from the roof of the Clean Air Facility at South Pole Station, centered on 7°W longitude, at about 1200 UT on April 29, 1992, using Kodachrome-64 film, exposure time approximately 7 min., aperture f/4, focal length unknown. Air temperature at the surface was -47°C. The print displayed here was made from a duplicate of the original slide, overexposed by a factor of 8 to enhance details that were too dark to see in the original (photograph by S.G. Warren).

h, at azimuth a relative to the Sun, is computed using equations 3.1-3.4 of *Gadsden and Schröder* [1989] and is plotted in Figure 2 for clouds at heights h = 60, 70, 80, 90, and 100 km above the surface. This computation requires a correction for refraction of sunlight (Table 1) and an estimate of the "screening height" H, which we take as H = 15 km [*Gadsden and Schröder*, 1989, p. 25]. This means that sunlight passing closer to the surface than 15 km is assumed to be attenuated too much to illuminate the cloud. For the solar depression of 14.6°, the cloud must be at least 56 km above the surface to be observed as sunlit on the horizon. The boundary between sunlight and twilight on the cloud (comparing Figures 1 and 2) indicates that the cloud is located at $h \approx 80$ km above the surface. (For this estimate the left side of the photograph is used, because on the right the sunlight/twilight boundary appears to be obscured by tropospheric clouds in the foreground.) However, the observing site, as well as the Antarctic Plateau for several hundred kilometers in the direction of view, is elevated about 3 km above sea level, so the cloud height above sea level is estimated as $h+3 \approx 83$ km, i.e., the same as for summertime NLCs [*Fogle and Haurwitz*, 1966]. This height estimate rules out nacreous clouds, which occur in the lower stratosphere at 15-25 km [*Kinne and Toon*, 1990].

Setting h = 80 km, the latitudinal extent of the cloud can be estimated by trigonometry. The part of the cloud on the horizon would be at a distance of 9° of latitude (1000 km). The cloud appears to extend in twilight at least to 5° altitude, where it would be 5° distant. The cloud therefore is estimated to extend latitudinally at least from 81°S to 85°S and longitudinally from about 40°W to 20°E.

The cloud disappeared after 2 hours of observation, as the Sun had moved west and ceased to illuminate it. This is a lower bound on the cloud's lifetime. All-sky camera observations might be used to determine how long the cloud had been visible before the observers went outside and noticed it. However, the all-sky camera operating at South Pole Station at that time had a field of view of only 160° (T. Berkey, Utah State University, personal communication, 1995), so would not see to the horizon. We cannot rule out the possibility that the cloud formed several days earlier than it was observed. During the previous five days April 24-28, strong winds lifted blowing snow that obscured the sky. The winds weakened and the blowing snow settled on April 29. If the cloud had formed near longitude 0°E on April 28 or earlier, it therefore would not have been seen until the Sun illuminated these longitudes near 1200 UT on April 29. The cloud was not observed on the following day (April 30).

Conditions for Observation of Noctilucent Clouds at the South Pole

The fact that only this one event was observed in the 1992 dark season at the south pole does not mean that NLCs are as rare as one in six months. NLCs cannot be seen at solar depressions $\beta<6°$ because the twilight is too bright, and at

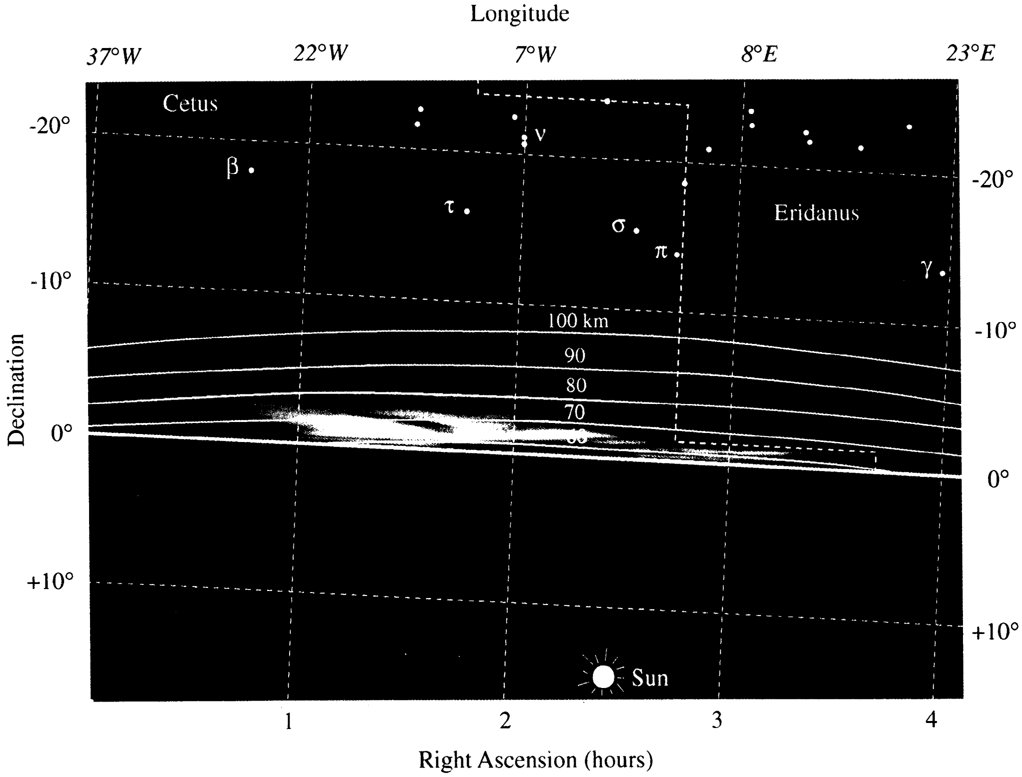

Figure 2. Interpretation of the photograph. The horizon is tilted because the camera was not leveled. Nineteen identifiable stars in the constellations Cetus and Eridanus are indicated. The brightest star is β-Ceti in the top left. The dashed line indicates the boundary between the two constellations. The boundary line between sunlight and twilight is indicated, as it would appear on clouds at five different altitudes (60, 70, 80, 90, 100 km).

$\beta>16°$, they cannot be illuminated at 83 km [*Fogle and Haurwitz*, 1966]. The periods of time with $6°<\beta<16°$ at the south pole are April 5 to May 3 and August 9 to September 6, a total of 58 days. During winter 1992 the sky was obscured by blowing snow about one third of the time, and the average (tropospheric) cloud cover during nonblizzard observations is about 30% [*Hahn et al.*, 1995, Figure 13b]. The fraction of time during the 6-month dark season during which a NLC could be observed if present is therefore about 13%. Considering only the month of April (after April 5), the cloud conditions and blowing-snow conditions would allow observation of NLC about 40% of the time.

Nature of the Cloud

The height estimate was made by assuming that the near-horizon part of the cloud was illuminated by direct sunlight. Alternative possibilities are moonlight or refracted sunlight. Moonlight can be ruled out because the Moon was in its crescent phase, 4.5° below the horizon and only 40° in azimuth from the Sun. Furthermore, this cloud appeared much brighter than tropospheric clouds illuminated by the full Moon. With regard to refracted sunlight, the extreme maximum refraction ever observed is about 5°, in the Novaya Zemlya solar mirage [*Meinel and Meinel,* 1983], but during the NLC event, the Sun was much farther below the horizon. Furthermore, when large values of refraction angle are observed, they are caused by refraction below the screening height, so the refracted light intensity would be too weak to illuminate a cloud. Above the screening height, only fractions of a degree of refraction are possible (Table 1).

Another possibility would be that the event was not a cloud but an aurora. However, auroral displays change their appearance much more rapidly than was observed for this event. Also, the orange color observed is more typical of twilight than of aurora. Furthermore, the bright region moved west with the Sun, consistent with the Sun setting on the eastern part of the cloud as it rose on the western part.

We conclude that the sighting was of a sunlit cloud at mesospheric height, of lifetime probably 2-24 hours, but its composition and origin are not yet established. The possible explanations fall into two categories: (1) a water-ice cloud produced by injected water from a rocket or a meteor, or by an anomalous atmospheric cooling event, and (2) a dust cloud resulting from a reentering artificial satellite, a rocket, or a meteor.

Water-Ice Cloud

In this section we will consider various sources of water vapor, ending with the conclusion that regardless of the source of water vapor a water-ice cloud is possible in April only if the 83-km temperature is at least 70 K below normal.

Artificial NLC have been frequently sighted after the launch of a rocket [*Benech and Dessens*, 1974; *Meinel and Meinel*, 1983, plates 9.2-9.3; *Sandford*, 1986; *Kalv*, 1989]. The formation mechanism is not understood, since such clouds can occur in regions that are far too warm for saturation. These artificial clouds normally appear as narrow streaks, not like the broad expanse of cloud shown in

Table 1. Solar Depression Angle for Computation of Sunlight/Twilight Boundary on a Noctilucent Cloud

Contributions to Apparent Depression Angle	Angle (degrees)
Solar declination, 1200 UT, April 29, 1992, from *Boksenberg and Hagen* [1990]	14.63°
Refraction of the incoming beam down to the screening height of 15 km, and then up to 80 km [*Gadsden and Schröder*, 1989, Table A1.2]	0.10°
Refraction of light from a cloud at 80 km, down to the surface at a viewing angle of 2.5° and surface pressure of 690 mbars [*Boksenberg and Hagen*, 1990, p. 280; *McCartney*, 1976, Table 2.9]	0.20°
Radius of Sun	0.27°
Apparent depression angle of upper limb of Sun	14.06°

Figure 1. In any case we can reject this possibility because there is no rocket-launching facility in the Antarctic, and to our knowledge no rockets were fired from portable launch facilities during the winter of 1992.

The second possibility is that a meteor injected water into the region, sufficient to saturate the cold mesopause. To estimate the amount of water needed, we note that to double the normal mixing ratio of 2 ppmv over a volume of 500 km by 500 km by 1 km would require a water mass of 2900 kg. Meteoroids typically contain 10-20% water (D. Brownlee, personal communication, 1995), so the required total mass is 15-30 tons. According to *Shoemaker* [1983, Figure 1], about 10 meteoroids of this size enter the atmosphere every year. Thus from this point of view this mechanism is plausible.

The more sensitive constraint for ice formation is not the available water but the ambient temperature at the cloud height. The temperature must be low enough for the region to be close to saturation. We show in Table 2 the required water mass needed to attain saturation, for various temperatures, and the frequency of impact of meteoroids containing this much water. It is clear from Table 2 that only for temperatures <150 K is the probability high enough for this to be a plausible mechanism.

In the absence of an injection, still lower values of temperature are needed for ice crystals to be stable: at 83 km, where the total atmospheric pressure is 0.4 Pa, 2 ppmv of water vapor implies a frost point of 142 K. The mesopause temperature at 80°S in late April is normally about 230 K, according to both the COSPAR International Reference Atmosphere (CIRA) model [*Fleming et al.*, 1990] and to recently analyzed data from the pressure modulating radiometer (PMR) [*Lawrence and Randel*, 1996]. Thus to support a water-ice cloud, the atmosphere must have been abnormally cold in late April 1992, whether or not there was a meteoroid injection.

Significant mesospheric cooling is known to occur during stratospheric warming events [*Andrews et al.*, 1987]. Also, a rapid cooling in the OH airglow rotational temperature at 90 km during early April in the northern hemisphere (70°N) of nearly 50 K has been observed to occur over a four-day period [*Myrabø and Harang*, 1988]. These authors reported that on an hourly basis, fluctuations of ±50 K or more have been observed at high latitude during the spring months. Tidal amplitudes are of the order of 5-10 K. Whether such fluctuations occurred over Antarctica in April 1992 and whether these are sufficient to produce water-ice will now be considered.

Just taking the difference between the climatological mean temperature at 80°S (230 K) and the frost point at 83 km (~140 K), it would appear that a cooling of 90 K is needed to reach saturation. However, this estimate ignores systematic errors in the temperature measurements made by the PMR instruments, or indeed most remote sensing determinations which average over a considerable vertical depth (5-10 km). In addition, simple arguments based on saturation are probably not the full story. Rocket measurements show that the temperature at the height of simultaneously measured NLC (83 km) is consistently 150 K [*Lübken et al.*, 1996]. Saturation at this temperature would require 11 ppmv of water

Table 2. Amount of Water Required to Achieve Saturation at 83 km at Various Temperatures, and the Meteoroid Mass Required to Deliver This Much Water

Temperature (K)[a]	Saturation Vapor Pressure (Pa)[b]	Water Vapor Mixing Ratio[c]	Water Vapor Mass (tons)[d]	Total Mass (tons)[e]	Kinetic Energy (J)[f]	TNT equiv. (MT)[g]	Frequency (yr^{-1})[h]
140	4.5×10^{-7}	1.1×10^{-6}	0	0	0	0	--
150	7.0×10^{-6}	1.8×10^{-5}	22	150	4.4×10^{13}	0.011	1
160	9.7×10^{-5}	2.4×10^{-4}	325	2200	6.3×10^{14}	0.15	0.1
170	7.7×10^{-4}	1.9×10^{-3}	2440	16000	4.6×10^{15}	1.1	0.02
200	0.16	0.4	4.3×10^{5}	3×10^{6}	8.6×10^{17}	210	3×10^{-4}

[a]Temperature at cloud height (83 km).
[b]Saturation vapor pressure was measured by *Bryson et al.* [1974] for 140-170K, and reported by *West* [1981] for 200K.
[c]Saturation mixing ratio, assuming total pressure is 0.4 Pa.
[d]Additional mass of water required to saturate a volume 500x500x1 km^3, assuming that 2 ppmv of water vapor is already present.
[e]Total mass of meteoroid containing 15% water.
[f]Assuming an initial meteoroid speed of 24 km s^{-1}.
[g]One megaton of TNT is equivalent to 10^{15} calories.
[h]Frequency of occurrence of meteoroids of these energies, using the "best estimate" curve in Figure 1 of *Shoemaker* [1983].

vapor, considerably more than measured by the Halogen Occultation Experiment (HALOE) instrument on the Upper Atmosphere Research Satellite (UARS) [*Russell et al.,* 1993], and even more than is expected from the total hydrogen content of the middle atmosphere. A better approach, which uses only temperature differences, relies on the fact that polar mesospheric clouds (PMC) occur only during certain times of year at certain latitudes. If we determine the temperatures prevailing during the PMC "season," we can then ask whether conditions were similar in late April 1992.

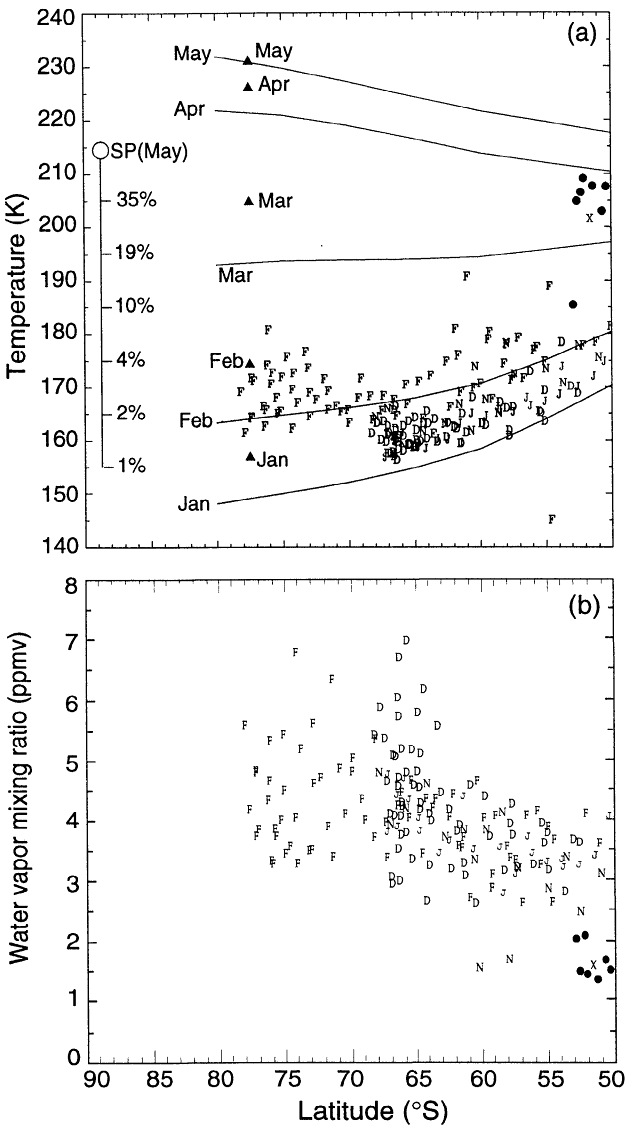

Figure 3. (a) Daily averaged temperature and (b) water-vapor mixing ratio at the 0.4-Pa pressure level (approximately 83 km). Data are from the HALOE solar occultation experiment [*Russell et al.,* 1993] onboard the UARS spacecraft. All available data for the 4-year period 1991-1995 are shown for latitudes south of 50°S and for the four summer months of November (N), December (D), January (J), and February (F). Solid circles, daily-averaged values from the period April 28 to May 6, 1992. (Value for 29 April is shown as X.) Solid curves, Figure 3a, CIRA model temperatures for the 5 months January to May. Solid triangles, Figure 3a, monthly averaged temperatures at 83 km from pressure modulating radiometer (PMR) for January to May at 77.5°S. Figure 3a also shows the average (open circle labeled "SP (May)") and negative deviations of the Fabry-Perot Doppler temperature measurements at 88 km in May at the south pole (discussed in text). The percent values indicate the fraction of time that temperatures below that level occurred in May (from Figure 4).

Data from instruments onboard the Solar Mesosphere Explorer (SME) spacecraft provided good statistical information on southern hemisphere PMC occurrence during the years 1981 to 1986 [*Thomas and Olivero,* 1989]. PMC were found to occur poleward of 55°S between November 20 and February 20 at a mean height of 83 km. Until recently, neither temperature nor water vapor data were available for these latitudes. Recently several data sets for temperature, and one data set for water vapor, have become available (although none exactly coincident in time and space). Of those available, three are valuable in assessing the temperatures necessary for PMC occurrence. The PMR provided temperature data in the late 1970s near the Antarctic mesopause where the CIRA model relied upon interpolation in this region. HALOE provided both temperature and water vapor information during late April 1992 but only at lower latitude. These data are useful in determining whether the atmosphere at 50°S was anomalously cold during that period. In addition, ground-based measurements from the South Pole Station of the Doppler temperature of OH airglow lines (emission from a mean height of 88 km) are available since 1990 [*Hernandez et al.,* 1992a,b, 1993]. These measurements begin in May of each year near the end of astronomical twilight (18° solar depression angle).

The monthly averaged PMR data at 80°S [*Lawrence and Randel,* 1996] suggest that PMC occur at temperatures below 160 K, based on the beginning date for the cloud season. On the other hand, the temperatures rise to 175 K by the time clouds disappear at the end of the season. We first examine HALOE data for temperature and water vapor to determine whether daily averaged values were significantly different in April 1992 at 50°S. Figure 3 shows measurements taken over 4 years (1991-1995) over the latitude range 50°-80°S for the 4 months centered on the summer solstice. In assessing the temperature needed for PMC formation, it is important to note that PMC are always patchy and are likely to be present only at the coldest locations. Thus a conservative interpretation of Figure 3 is to take the lower envelope of temperature and the upper envelope of water to be indicative of cloud existence. To be still more conservative, only the two coldest months (December and January) will be considered. At the PMC boundary (55°S) the lower envelope is about 165 K. Thus we would expect clouds to occur "naturally" (i.e., without a meteoroid injection of water) if the temperature is below a critical value of 165 K. In the same way we estimate that the water vapor at 83 km should exceed 4 ppmv for PMC to form. However, the high water amount is not nearly as critical as the low temperature.

The daily-averaged conditions measured by HALOE during late April 1992 are also plotted in Figure 3 but are available only as far south as 55°S. It is clear that the mesosphere was considerably warmer and drier during this period than during November-February. The HALOE temperatures agree with the climatological (CIRA) model during the PMC season and are about 10 K colder than the CIRA model during the April-May period. Thus we conclude that there was no large-scale cooling event during late April

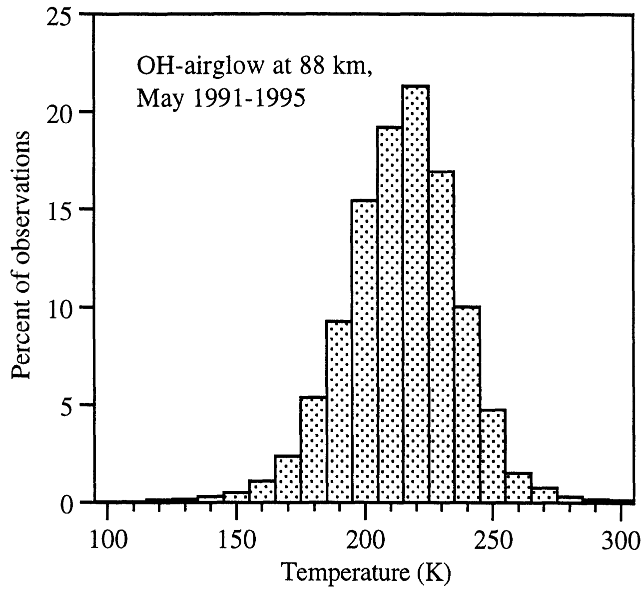

Figure 4. Frequency distribution of temperatures at about 88-km altitude, from airglow emission by OH, for May 1991-1995, measured from the surface at South Pole Station. The data cover approximately the period 10-31 May, with more data toward the end of May. Temperatures are obtained from ground-based observations of the Doppler width of the natural emission from the OH radical [*Hernandez et al.*,1992a,b, 1993]. The OH layer height of emission has been measured at high latitudes to be near 88-km altitude [*Witt et al.*, 1979]. The measurements begin in May of each year and end sometime in August, when the sky background due to twilight illumination overwhelms the observations. The actual measurements consist of the observation of the lambda-doubled P1(2) line of the (6-2) band of OH at 840 nm. Since the optical measurements are also made to determine wind motions, the observations are made at eight equally spaced azimuthal directions at 60° zenith angle as well as the geographic zenith. The time required for observation of a nine-position sequence is typically about 75 min. This nine-position observational sequence continues indefinitely for the duration of the polar night at the south pole. This figure consists of all the available measurements for the months of May. Doppler-width-derived temperatures appear not to be significantly affected by the presence of clouds [*Smith and Hernandez*, 1995]; thus no selection for weather conditions has been made. Frequency of temperatures below 145 K is 0.6%; below 155 K, 1.1%; below 165 K, 2.1%, and below 175 K, 4.5%. These percentages are upper limits because the histogram is of the actual temperatures measured. Each temperature is subject to an uncertainty, so the histogram plotted here is broadened from the true shape.

1992 that would bring 83-km temperatures down to summer values. We confirmed that no stratospheric warming occurred during this period by examining the synoptic maps of the southern hemisphere geopotential height and temperature fields at 10 mbar (30 km) for several days surrounding the NLC event. Nothing unusual was apparent in either field. The temperature in the region below the cloud at the time of the NLC sighting was only 4 K higher than at 12 hours before and after.

We now consider the OH temperature measurements made at the south pole. Measurements are not available for April, because the background light from residual twilight is still too bright for accurate measurements until mid-May. We therefore examine the temperatures for May, as the closest nearby month for which data are available. The statistical distribution of temperature for the month of May, from 1991 to 1995, is displayed in Figure 4. The histogram shows that in middle-to-late May the temperature is below 165 K about 2% of the time (about 16 hours during a typical May). The percentages for late April are likely to be higher than those in May, because April is colder than May at near-mesopause heights.

Two examples of temperature in the cold tail of the histogram are shown as time series in Figure 5. Over a 4-hour period on May 28, 1994, the temperature dropped from 210 K to 130 K, then rose again to 210 K. A 3-hour period of low temperature is shown in August 1993. On some other occasions, we found that the low temperature is seen at only one of the viewing azimuths, indicating high spatial variability.

We cannot say for certain that the temperature was below 165 K during the time of the NLC sighting. It appears that small-scale cold "pockets" near the south pole (perhaps as large as 500 km by 500 km) could have occurred during this time period with a probability of 2%. Thus the mesosphere may have been near or above saturation during this time period. An addition of extra water by a meteoroid would not change this general conclusion, unless it were a truly massive object. Other effects of a large meteoroid entry are discussed below.

Dust Cloud

A noctilucent dust cloud might be produced either from a natural meteor event or from reentry and disintegration of an artificial satellite. Man-made orbiting objects are tracked by the North American Aerospace Defense Command (NORAD). Table 3, obtained from NORAD, lists the 22 objects that reentered the Earth's atmosphere during the month of April 1992. No information is available on the exact location of reentry, but the orbital inclination constrains the range of possible latitudes of reentry. The object entering on April 29 could not have entered over Antarctica. The object entering on April 27 could have entered over Antarctica, but its radar cross section indicates that it was very small. Explanation of the cloud as dust from a satellite reentry is anyway unlikely, as the 77-ton "Skylab," the largest man-made object ever sent into orbit, appeared on reentry after local midnight as a meteor shower (a series of short-lived bright streaks), but no sightings of a debris cloud were reported as sunrise approached [*Lyons*, 1979].

Reentry of an artificial satellite can therefore be rejected as a cause of the observed NLC. NORAD tracks only man-made objects, so there remains the possibility that the observed cloud consisted of debris from disintegration of a meteoroid. Inquiries about meteor-radar observations have not identified any such radar in operation in the Atlantic sector of Antarctica during 1992. However, we can specify what would be required for a meteor to be able to produce a noctilucent dust cloud.

We first ask how a very large (500 km x 500 km) dust cloud could result from a very narrow debris trail of a meteor. There are two possibilities.

1. The object may have entered the atmosphere in a grazing trajectory, leaving behind a horizontal debris trail, which

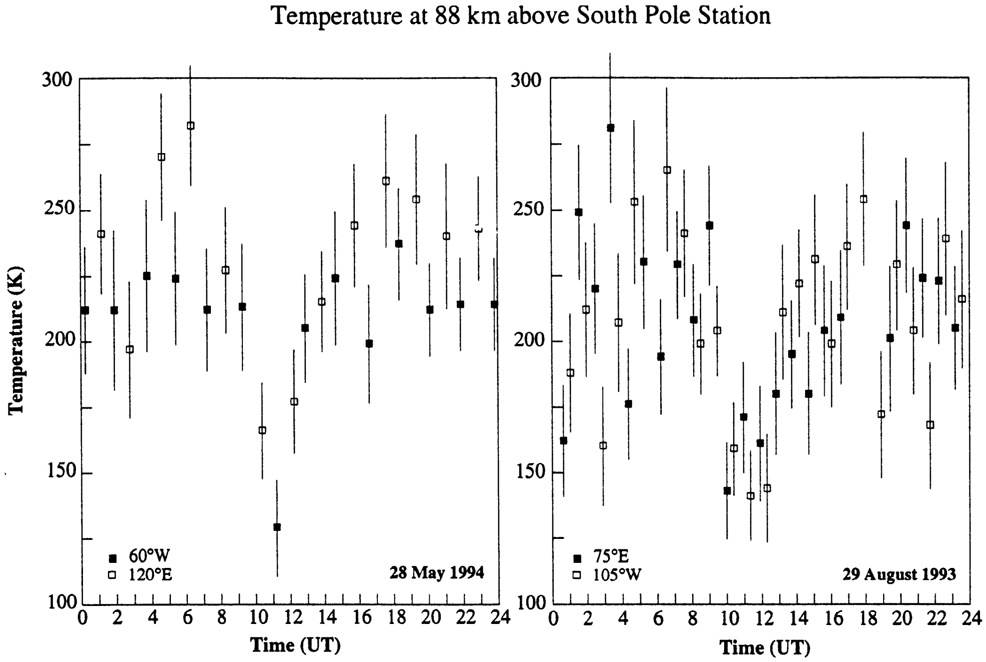

Figure 5. Time series of temperatures at 88 km at the south pole, on two winter days on which low temperatures were observed. Hourly values are shown for each of two viewing azimuth angles 180° apart. The viewing zenith angle is 60°. The low temperatures were observable at only two azimuths, out of the eight observed directions. The other directions are not shown in the figure to avoid obscuring the observed sharp change.

subsequently spread laterally because of wind shear. Such an event occurred on August 10, 1972, when a daytime fireball was witnessed over Utah, Idaho, and Montana, reaching a perigee of 58 km and then returning to space after its last sighting over Alberta [*Rawcliffe et al.*, 1974]. Estimates of its mass range up to 4000 metric tons [*Jacchia*, 1974]. However, its trail became invisible after 1 hour, and Jacchia's summary of all available observations made no mention of any noctilucent cloud after sunset on that day in the vicinity of the event.

2. Alternatively, the trajectory was steeper and the meteoroid detonated much deeper in the atmosphere. Debris would then be lofted into the mesosphere within the cylindrical cavity created in the wake of the meteor. This high-altitude dust injection mechanism is now believed to have caused the widespread sightings of bright skies following the famous event of June 30, 1908, at Tunguska in Siberia (O.B. Toon, personal communication, 1996). Both NLC and unusual sky brightness were observed for several days after the fall [*Turco et al.*, 1981, 1982]. However, that event occurred in the middle of the normal NLC season with low mesopause temperatures, so the observed NLC may have consisted mostly of water-ice contributed by the meteoroid, with only a small part of the scattering due to the dust.

Beginning about 1975, U.S. military satellites have been used to detect meteor impact events ("fireballs"). They are detected either by thermal infrared emission at night or by reflected sunlight in daytime [*Tagliaferri et al.*, 1994]. A map showing the 136 significant events detected between 1975 and 1992 is shown in their Figure 7. No fireball events were recorded on April 29, 1992; however, the authors estimate that only about one quarter of fireball events are recorded by their data system. None of the 136 fireballs has been associated with a report of NLC sighting (M. Boslough, personal communication, 1995). However, we will proceed with the hypothesis that the cloud shown in Figure 1 consisted of meteoritic debris and we will estimate its mass and thus the inferred fireball mass.

We assume that the cloud particle size distribution is determined from gravitational sedimentation occurring over a time period 2-24 hours (the estimated lifetime of the cloud observed at the south pole). Integrating the numerical formula for the sedimentation velocity [*Fogle and Haurwitz*, 1966] in a static, nonturbulent atmosphere from height z_1 to z_2, we find the fall time t (in seconds) to be $t = (0.347 / r\rho)$ $[p(z_2) - p(z_1)]$, where r is the effective particle radius in micrometers, ρ is the particle bulk density in grams per cubic centimeter, and p is the pressure in pascals. We evaluate the time that a cloud particle spends above the shadow line (so that it is visible), which is the time to fall about one scale height. The above formula becomes, on evaluating the lifetime in hours at 0.4 Pa (83 km), t (hr) $\approx (r\rho)^{-1}$ to within 4%. For $2<t<24$ hr, and assuming $\rho = 2$ g cm^{-3}, particle radii are limited to the range 0.02-0.25 μm. This range also encompasses the range of visible NLC particles (r<0.07 μm), which is no surprise, since their sizes are also determined largely by sedimentation [*Jensen and Thomas*, 1988].

We now estimate the concentration and mass of dust particles required to produce a visible dust cloud. We assume that the scattering coefficient σ_c of the cloud is 10 times that of the surrounding air, σ_{air}. (The available lidar data show that scattering ratios σ_c/σ_{air} go from several to more than 100 for typical summertime NLC [*Langer et al.*, 1995].) Assuming Mie theory is valid for small, irregular particles (justified by *Thomas and McKay* [1985]), we obtain the constraint on the dust concentration, $n_{dust} > 10\ \sigma_{air} / \pi r^2 Q_{sc}$,

Table 3. Man-made objects re-entering the atmosphere during April 1992 (from S. Boylan, NORAD, personal communication, 1995).

Satellite Name	Owner[1]	Reentry Date (April 1992)	Inclination of Original Orbit (deg)	Radar Cross Section (Unspecified Units)
SL-12 plat	CIS	02	52	15.80
STS-45	US	02	57	39.15
SL-4 R/B	CIS	04	67	0.00
MIR deb	CIS	04	52	0.51
SL-12 R/B (1)	CIS	04	52	13.70
MIR deb	CIS	05	52	0.07
SL-12 R/B (aux motor)	CIS	06	47	0.60
COSMOS 2107	CIS	06	65	20.18
SL-12 R/B (aux motor)	CIS	09	48	0.31
SL-4 R/B	CIS	10	65	14.00
MIR deb	CIS	11	52	0.23
COSMOS 2027	CIS	14	66	3.63
SL-12 R/B (aux motor)	CIS	16	48	0.31
DELTA 1 deb	US	17	98	0.12
COSMOS 1823 deb	CIS	18	73	0.53
COSMOS 397 deb	CIS	18	66	0.09
SL-4 R/B	CIS	21	52	21.87
ARIANE 44LP R/B	ESA	21	07	0.60
MIR deb	CIS	21	52	0.48
SL-8 deb	CIS	23	74	0.01
COSMOS 1275 deb	CIS	27	83	0.01
COSMOS 1461 deb	CIS	29	65	0.07

[1]CIS, Commonwealth of Independent States; ESA, European Space Agency; US, United States.

where Q_{sc} is the scattering efficiency and $\sigma_{air} = 1.3 \times 10^{-11}$ m^{-1} at wavelength $\lambda = 0.5$ µm. Choosing $r = 0.05$ µm as representative of the range 0.02-0.25 µm, we find from a Mie-scattering calculation a value $Q_{sc} = 0.03$, which yields the inequality $n > 0.55$ cm^{-3}. The required mass density is $> 5.8 \times 10^{-16}$ g cm^{-3}, and the total cloud mass is $M > 140$ kg if the cloud fills a volume 500x500x1 km^3. The diameter of the hypothetical meteoroid is then ~0.5 m. Since Q_{sc} varies as r^4 for the smaller sizes (i.e., for $r \ll \lambda$), and mass is proportional to $r^3 n$, the total mass will scale according to $(0.05/r)^3$ if $r <$ 0.05 µm. We consider the upper limit on required cloud mass to be determined by the particles of longest lifetime ($r = 0.02$ µm), so that $M < 2200$ kg. The corresponding diameter is 1.3 m.

In summary, if the object ablated completely above 83 km, the cloud could have been caused by a meteoroid of approximate mass 100-2000 kg. (However, much larger size would be required if the meteoroid penetrated more deeply into the atmosphere or if a significant fraction of the debris was of larger size that sedimented quickly.) Extrapolation from Figure 1 of *Shoemaker* [1983] indicates that the expected frequency of 2000-kg meteoroids is 50 per year, and of 100-kg meteoroids is 1000 per year.

We are not aware of any photographs of sunlit clouds of known meteoroid debris taken from the Earth's surface with which to compare our photograph. However, the cometary impacts on Jupiter in 1994 did apparently cause formation of noctilucent clouds. A sunlit high cloud is visible beyond the terminator in the lower image of Figure 2 (fragment G, frame 7) of *Hammel et al.* [1995], as discussed by *Boslough et al.* [1995].

Summary and Conclusion

In summary, a bright cloud seen from South Pole Station on April 29, 1992, was found to be at a height of about 83 km, the same height as noctilucent clouds. This cloud extended at least 500 km in both latitude and longitude. As possible explanations of the sighting, we have ruled out aurora, tropospheric clouds, nacreous clouds, and artificial NLC from a rocket or reentry of a man-made satellite. There remain three possible explanations.

1. Disintegration of a water-rich meteor (or small comet) in the upper mesosphere produced an excess of water, combined with an abnormally cold mesopause. The additional moisture would force the atmosphere into saturation, with the subsequent growth and sedimentation of ice particles. We reject this explanation since it requires the simultaneous occurrence of two rare events (Table 2).

2. A cold pocket of air formed in the normally warm (230 K) mesopause region, due possibly to a localized breaking gravity wave. Such a cooling mechanism has been modeled by *Fritts and Luo* [1995]. Regardless of the mechanism, the observational evidence for occasional large temperature excursions (± 50 K) is supported by ground-based measurements of the Doppler temperature of the OH airglow emission lines in the northern hemisphere, and ± 70 K at the south pole. This cold pocket of air became saturated, and an ice cloud was formed. Rare out-of-season NLCs have been reported in both the northern hemisphere [*Vasil'yev et al.*, 1974] and the southern hemisphere [*Griffiths and Shanklin*, 1987], so there is some observational support for this explanation.

3. A meteor deposited most of its debris in the 83-km region. The larger debris quickly vanished from the sunlit upper mesosphere, leaving behind 1-20 metric tons of small particles of radius 0.02-0.25 µm. These particles settled out of the mesopause region over the observed lifetime of the cloud (2-24 hours). The number of 1-kt-yield meteoroids that strike the Earth has been estimated by *Shoemaker* [1983, Figure 1] as 10 per year and by Tagliaferri (quoted by *Beatty* [1994]) as 80 per year. (A 1-kt yield corresponds to a 14-t object traveling at 24 km s^{-1}.) No fireball was reported by the

DOD space-based network on April 29, 1992. However, this is not surprising since the chances of detecting even bright fireballs are only about one in four [*Tagliaferri et al.*, 1994].

Explanations 2 and 3 seem to be the only ones possible, but we lack positive evidence for either of them. Explanation 2, an anomalous cooling event of limited spatial scale, is more likely. The reason we are skeptical about explanation 3 is not that multiton fireballs are rare but that their debris has never before been reported to form a noctilucent dust cloud outside the normal NLC season. The only previously reported association of NLC and bright skies with a meteor was the Tunguska event, which occurred during the normal NLC season.

We recommend that reports of fireballs should be promptly followed by organized searches for an ensuing sunlit cloud at the next several twilights. We further recommend that in future observational campaigns to study NLC and PMC, measurements not be confined to the summer season but also be made at other times of year. Out-of-season cloud occurrences could be associated with extreme weather events in the middle atmosphere, or even in the troposphere.

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