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TECHNICAL REPORT 181

ON THE ORIGIN AND CLIMATOLOGY OF NOCTILUCENT CLOUDS

By
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PREFACE

This report was prepared initially in response to a request from the X-20 Program Office, Aeronautical Systems Division, AFSC. The X-20 Office, in order to assess possible effects of noctilucent clouds on space vehicles, requested information on various properties of the clouds, including their frequency of occurrence as a function of latitude and longitude and time of year. In view of the growing interest in noctilucent clouds, both in meteorological and engineering circles, it seemed appropriate to make further distribution of this report.

There has been a recurring interest in noctilucent clouds during at least the past eight decades. This interest came into focus in the middle and late 1950's, with the implementation of several carefully designed observational programs. Direct sampling of cloud particles by rockets in 1962 provided a basis for checking theoretical estimates of particle size and concentration. With continued study, it is not unlikely that some of the still unanswered questions regarding noctilucent clouds can be resolved in the near future.

In this report a review is made of the existing concepts of the constitution or origin of the clouds, and a mechanism is suggested which might explain their apparent dependence on latitude. Their frequency of occurrence with respect to latitude, longitude, time of year, and other factors, is analyzed in detail. Year-to-year changes in the number of occurrences are considered in relation to the "11-year" sunspot cycle. A comprehensive sample of data on cloud movement is summarized, although in view of the highly complicated field of motion in noctilucent clouds, this subject is difficult to treat satisfactorily. Finally, a comparison is made of rocket samples of particle size and concentration with values deduced from polarization measurements by Ludlam [22] and Witt [43].

This report is another example of the growing AWS involvment in unconventional aspects of the upper atmosphere. It is hoped that in addition to providing useful information to the scientific community, the work reported may stimulate further interest among AWS meteorologists in the wider domain of aerospace environmental problems.

I wish to express my appreciation to Captain J. K. Lambert and 1st Lt. J. A. Dutton, of the Climatic Center, for many helpful comments, and to the staff of *Meteorological and Geoastrophysical Abstracts*, for making available a bibliography on noctilucent clouds before publication.

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1 August 1964

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SECTION A – INTRODUCTION

Noctilucent clouds have been talked about for decades, yet they remain one of the major mysteries of meteorology. Their origin and duration and their complex field of motion are foremost among the problems awaiting resolution. Recent investigations have provided partial answers; the complete solution may be close at hand.

The clouds are commonly assumed to occur at or near the temperature minimum which defines the mesopause, that is, near 80 km. Actually, they have been observed over a rather wide height band, from less than 75 km to 90 km (about 250,000 ft to 300,000 ft). As their name implies, they are seen at night, in the periods after sunset and before sunrise when the sun is 1 through 22 degrees below the horizon. They are observed mainly in summer, but they have been seen as early as mid-March and as late as mid-October. In the majority of the observations, the clouds have been seen at elevations of 1° to some 15° above the northern horizon, but in exceptional cases bands of noctilucent clouds have extended at least to the zenith.

A fair knowledge of the space and time distribution of noctilucent clouds is now available. For an empirical basis we have the early observations collected by Vestine [39] and later compilations by Störmer [36], Spangenberg [35], Ludlam [22], Witt [42], Gromov [12], Paton [27] [28], Astopovich [2], as well as the data from observational networks established in the U.S.S.R. in 1957 (Pavlova, [29]), and more recently in North America (Fogle, [8]). These data have been taken into account in determining basic climatological properties. A close look at the Soviet IGY results (1957-58) has proved especially worthwhile. Our results based on the total complex of data are given in sections D and E. The discussion refers to the Northern Hemisphere. Not much can be said on the basis of the few cloud reports available for the Southern Hemisphere.

A review of existing theories of the origin of the clouds is desirable for a proper appreciation of the climatological derivations. Section B is devoted to such a review. In the Northern Hemisphere noctilucent clouds have been seen only between latitudes 45° and 80°N. Section C describes a mechanism which might explain their apparent dependence on latitude.

This inquiry into the climatological properties of noctilucent clouds (hereafter abbreviated "NOC") has been made because of concern that the clouds, whether comprised of dust or some other material, might constitute a hazard to space vehicles. If the occurrence of NOC and the occurrence of critical dust concentrations near the mesopause are correlated, data on NOC should be useful for estimating hazards to space vehicles. The clouds appear to be truly latitude-dependent. If it can be shown that the concentration of dust does not depend on latitude, then the value of NOC information for vehicle hazard evaluation is open to question.

SECTION B – EXISTING THEORIES OF FORMATION

Several theories have been suggested to explain the presence of noctilucent clouds. These may be reduced to three basic propositions:

a. NOC consist of condensed water vapor in the form of ice crystals.

b. NOC consist of dust particles of either volcanic or extraterrestrial origin. An extraterrestrial source is favored, namely, secondary particles from meteor showers and from the background of sporadic meteors.

c. NOC consist of dust particles, of which at least some are surrounded by ice.

It is beyond the scope of this report to obtain proof or refutation of these propositions. However, evidence will be presented reflecting on the plausibility of each.

The question of condensation cannot now be answered definitively, owing to the absence of actual moisture measurements in the vicinity of 80 km. Assuming a mixing ratio by volume of 0.25×10^{-4}, or a vapor density at 80 km of $\sim 5 \times 10^{-13}$ gm/cm^3, Humphreys [18] calculated that condensation could occur at a temperature of 160°K. Ludlam [22] has noted that on the basis of soundings obtained by the British Meteorological Research Flight, the mixing ratio of 10^{-3} gm/kgm observed in the lower stratosphere tended to be preserved to higher levels[1]; this mixing ratio, if applicable at 80 km, indicates a vapor density at the latter height of 2×10^{-14} gm/cm^3 For condensation, the temperature corresponding to this moisture value is 145°K. At higher temperatures, the moisture content required for condensation should have to be appreciably greater. The possibility of a local moisture source is not excluded; Vegard [38] has suggested that water vapor might form from a combination of hydrogen with oxygen in the auroral regions.

As for the temperatures thus far observed at 80 km, rocket grenade observations have yielded values as low as 150°K (June) and 165° (late March) at Wallops Island, Va. (38°N), and approximately 170° (summer months) at Fort Churchill, Canada (59°N) (Nordberg and Smith, 26]; Stroud *et al.* [37]).[2] See Figure 1. Thus, the available evidence indicates that condensation is possible, at least in the summer months.

Regarding Proposition *b*, the fact that both the Krakatoa volcanic eruption of August 1883 and the Great Siberian Meteorite of June 30, 1908 were followed by a large number of reports of NOC immediately suggests that volcanic eruptions and/or meteors may provide a dust source.[3] When NOC occurrence is compared with other volcanic events, no evident relation emerges. This point has been treated in detail by Ludlam [22] and will not be discussed further here.

The case for meteors is more intriguing. Bowen [4] claimed to have found a close relation between the occurrence of NOC and recurrent meteor showers. His claim is unconvincing, in view (among other factors) of significant gaps in Vestine's collection of cloud reports, which Bowen used as a basis for comparison. Ludlam, considering further the controlled series of cloud observations at Torsta, Sweden (1954-55), found no clear relation between the occurrence of NOC and the arrival of meteor showers.

Note should be made, however, of the relative contributions of meteor *showers* and sporadic meteors to the total meteoric mass entering the earth's atmosphere. During major meteor showers the influx rate may increase by several orders of magnitude, over the background

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[1] For a more detailed consideration of observed moisture content to 30 km and implied frost points at 80 km, see Hesstvedt [16].

[2] A temperature in the vicinity of 135°K, the lowest ever recorded in the earth's atmosphere, was obtained in a rocket sounding in Sweden, summer 1963 (verbal communication from W. Smith, NASA).

[3] Although dust from Krakatoa was visible over Europe within 3 months after the eruption, the first reports of NOC were not until almost 2 years later. In contrast, NOC were visible almost daily during the two weeks following the meteor event. In much of Siberia, Soviet Central Asia, and eastern Europe, the clouds of June 30 were of exceptional brightness and were seen "all night long", according to Astapovich's [2] compilation of reports; Shenrok [32] cites 63 observations. Above the NOC, red-green cloud connected with the fall of the meteor was seen.

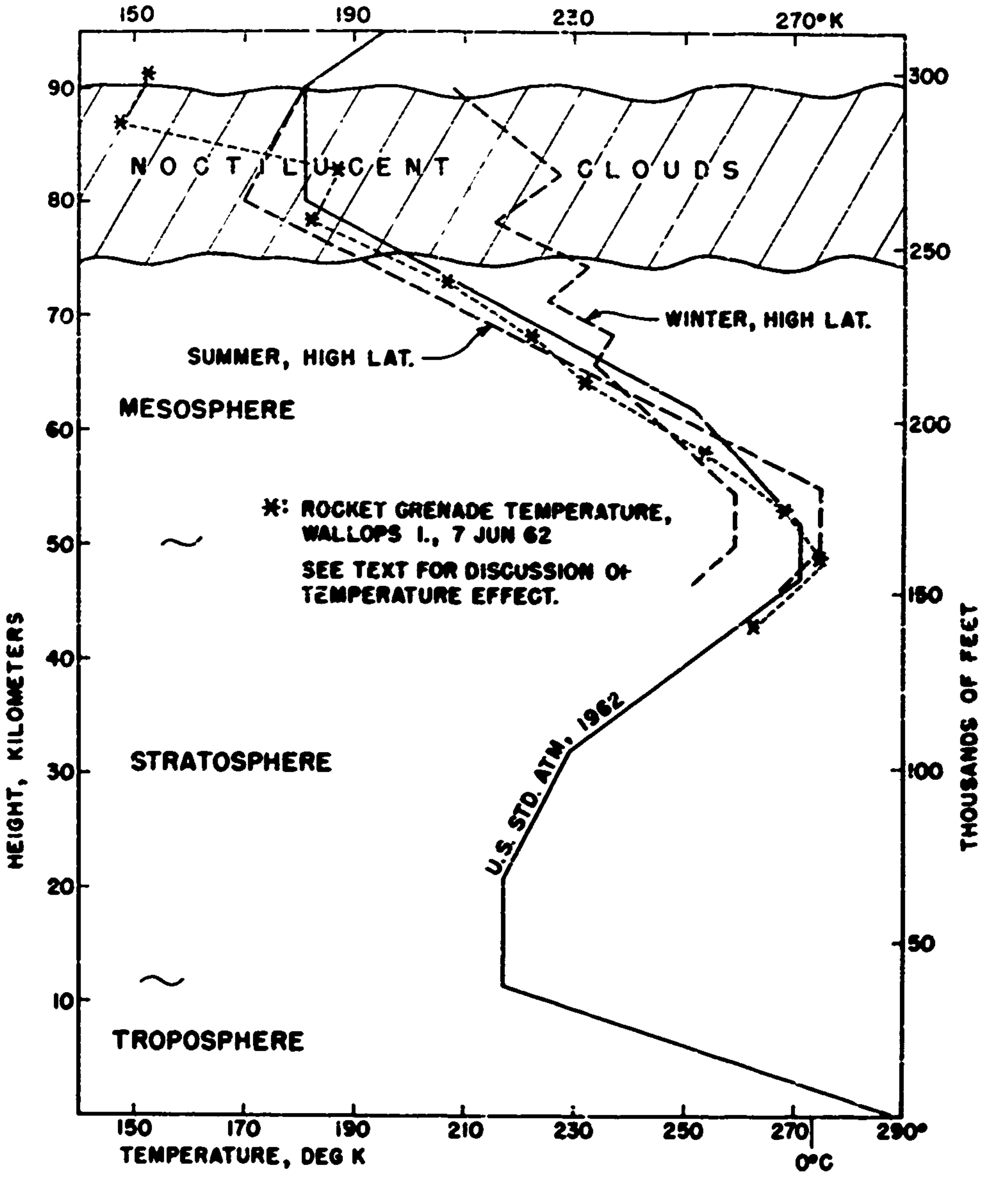


Figure 1. Height Region of Noctilucent Clouds Compared With Typical Atmospheric Temperature Curves (Broken Lines).

rate of sporadic meteors. But the mass contributed by major showers, estimated at 130 × 10^3 kgm. per year (Table IV, Greenhow and Lovell, [9]), is only slightly more than 20% of the total from all meteors (615 × 10^3 kgm per year). If a correlation is to be found between the occurrence of NOC and meteor activity, then the background rates or the combined background and shower rates of meteor influx should probably be taken into account.

Attention has already been called (Witt, [42]) to the general increase in meteor activity in summer, which is consistent with the high summertime frequency of observed NOC. It seems clear that any further comparison will require a detailed consideration of diurnal, day-to-day, and year-to-year fluctuations in meteor activity. Evidence of year-to-year variations in the post-IGY period has been presented by Millmann and McIntosh [25]. Diurnal behavior has been depicted by several authors. Figure 2 shows curves of monthly mean meteor counts as a function of time of day. These curves, reproduced from Millmann and McIntosh, were derived from a preliminary analysis of radar counts obtained at Ottawa, Canada, 1957-1960.

It is apparent from Figure 2 that a comparison of NOC occurring, say, in the evening hours with meteor counts at 19 and 07 hours would not yield similar results. Further, it is expected that time lags in the redistribution of particles of different sizes, due to variable initial meteor speeds and to natural vertical motions in the atmosphere, should increase the complexity of the problem.

Proposition *c*, "NOC consist of dust particles surrounded by ice", depends, of course, on the fulfillment of Propositions *a* and *b*, that is, dust, probably of extraterrestrial origin, must be available and conditions near 80 km must be favorable for condensation. Tentative evidence of ice-coated dust has recently been

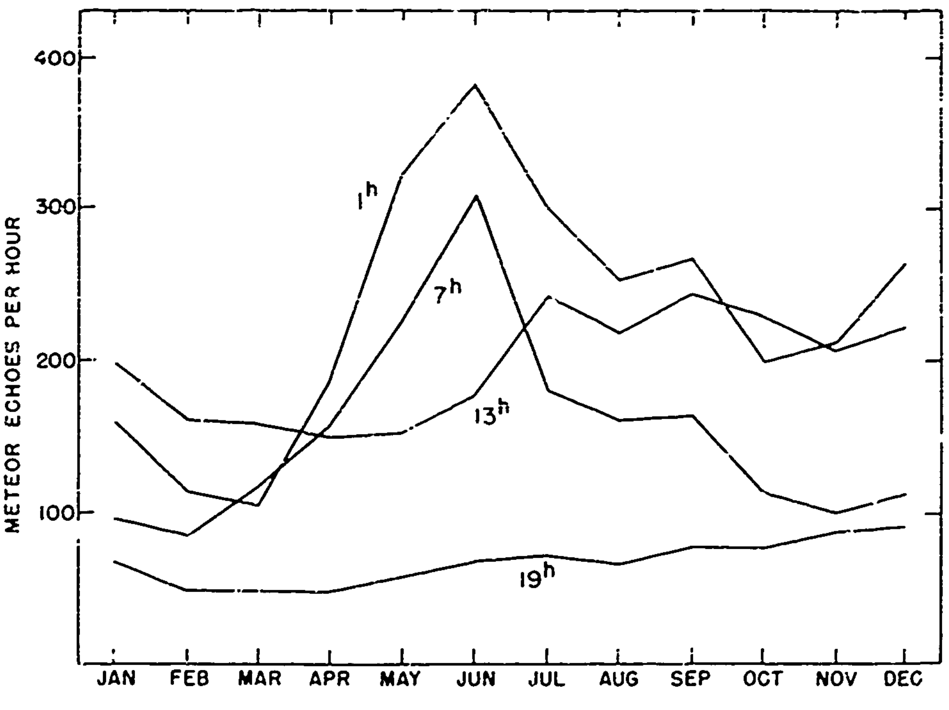


Figure 2. Monthly Radar Meteor Counts at 4 Hours of the Day (EST). From Millmann and McIntosh [25].

obtained in Sweden (Soberman,[34]). In the summer of 1962, particle counts were obtained with the aid of specially-designed rockets on one night when NOC were present and on one cloudless night. The rocket that traversed the NOC collected 10^2 to 10^3 times the number of particles collected by the rocket flown on a cloudless night. From a laboratory study of these data it was found that part, at least, of the cloud substance was solid and not volatile, and that about 10% of the NOC particles were surrounded by a coating of some substance that later evaporated, apparently ice. On the basis of this sample alone, one might conclude that noctilucent clouds indicate a large increase in dust concentration near the mesopause. Since only 10% of the particles sampled indicated a condensation process, the question remains as to whether condensation is necessary for the dust clouds to be seen.

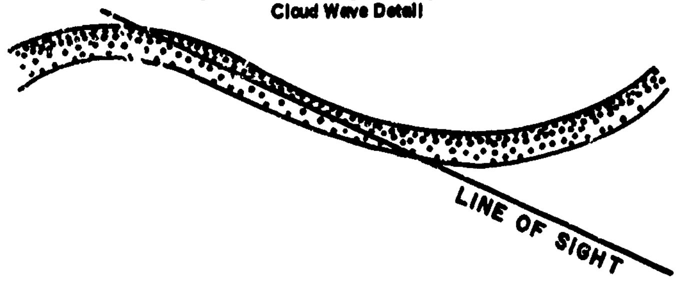
SECTION C — A POSSIBLE EXPLANATION OF NOCTILUCENT CLOUD FORMATION

As we have seen in the preceding section, condensation in the vicinity of the mesopause is possible; it may or may not be required for noctilucent clouds to exist. Whether or not condensation takes place, it will be assumed that a sufficient dust concentration must be available. The dust particles may act as condensation nuclei or may themselves have the scattering properties necessary to reflect the sun's rays for solar depression angles (ψ) in the range $\sim 6° < \psi < \sim 18°$.

The problem then reduces to describing suitable mechanisms for creating a dust layer, not necessarily continuous in time or space, in the vicinity of 80 km and at latitudes where NOC have been observed, from ~45° to at least 80°. (Until a few years ago, 65°N was considered the northern limit of visible NOC. The results of systematic observing programs in the middle and late 1950's have shown occurrences at higher latitudes. For example, two occurrences were noted at Bukhta Tiksi, 80° 20'N, 52° 55'E., in 1957-58.) The concentration of dust particles in this layer must exceed a critical value which permits their observation as "cloud" from the earth's surface, under optimum viewing conditions. The optimum condition may include a wave arrangement of the dust layer such that the observer's line of sight passes through a maximum number of particles (Figure 3). A wave motion, at times active and complex, is found in many NOC formations, particularly in very bright NOC (Grishin, [11]).

Assuming a suitable dust source, we know of no reason for expecting an influx that is latitude-dependent, except as discussed below; thus we further assume that the dust particles are initially uniformly distributed with respect to latitude. Ludlam [22] has pointed out that if interplanetary dust such as in the zodiacal-light cloud contained a substantial proportion of iron, or if it were charged by solar radiation, it "might enter the earth's atmosphere preferentially in high latitudes, thereby locally increasing in concentration".

Figure 3. Line of Sight Through Noctilucent Cloud Wave Detail



However, the direct contribution from interplanetary dust, as distinct from dust accrued by secondary scattering from meteors entering the earth's atmosphere at tremendous speeds (generally ~10 to 50 km/sec) may be quite small. Whipple [40] and Dubin and McCracken [6] have estimated that the spatial density of dust in the vicinity of the earth is 10^2 to 10^3 times greater than in the zodiacal cloud. If dust from any extraterrestrial source is considered, a latitudinal accumulation is still not excluded, according to Witt [42]. Assuming that charged dust particles with velocity 30 km/sec (a characteristic meteor velocity) enter the earth's atmosphere, Witt calculates that in accordance with the theory of motion of a charged particle in the magnetic field of the earth, certain particles would never reach the geomagnetic equator. Greater knowledge of the behavior of dust particles in the earth's magnetic field is needed before the question of their latitudinal dependence at all heights of the atmosphere can be resolved.

Assuming that particles below about 90 km are not charged or that the influence of the earth's magnetic field is negligible, we can look to two factors that would lead to increased concentrations in the neighborhood of the mesopause and at middle and high latitudes.

One is the relative thermal instability of the mesosphere in summer, permitting significant vertical motions, in contrast to the general stability characteristic of winter in middle and high latitudes (see Figure 1).

Above 80 km there is a return to thermally stable air so that the relatively large vertical motion expected in summer is not sustained above the mesopause. The summertime vertical profile of vertical motion, therefore, should lead to a concentration of dust particles in the vicinity of the mesopause, for those particles that are sufficiently light to be carried upward by ascending air. In winter, upward motion is inhibited throughout much of the mesosphere, and the same opportunity for the formation of a persistent dust layer at the mesopause is not expected to exist.

The second factor, not mentioned by previous authors, is the northward convergence of the streamlines suggested by low-latitude observational data on the meridional circulation. At such locations as White Sands, New Mexico (32°N) and Cape Kennedy, Florida (28°N), winds measured with the aid of rockets frequently have components from the south. At White Sands, for example, the mean southerly component, in both summer and winter, is of the order of 5 to 20 m/sec, at heights from about 60 to 80 kilometers. (In general, however, the mesospheric zonal components are much stronger than the meridional components.) If a southerly wind component of, say, 10 m/sec is assumed to prevail from latitudes ϕ_1 to ϕ_2, then estimates can be obtained of the time required for air and dust particles to reach ϕ_2 and of the relative particle concentration expected in a unit area centered on ϕ_2. The effect of increasing concentration with increasing latitude is depicted schematically in Figure 4. The area determined by the same interval of latitude and longitude is a function of cos ϕ. The total particle concentration, and along with it the dust concentration, should increase northward[4] as long as the meridional circulation does not undergo a significant change. For a sustained southerly component of 10 m/sec, for example, dust particles starting from 20°N would require about 3 days to reach 45°N and would have a concentration approximately twice as great at 45°N as at 20°N.

Of course, such ideal behavior does not necessarily occur in nature. Synoptic and diurnal fluctuations in the general circulation greatly complicate the picture. Indeed, such fluctuations, together with fluctuations in the thermal stability of the mesosphere and variations in the influx of extraterrestrial dust particles, are consistent with the intermittent character of observed NOC. It remains to point out that

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The total atmospheric density at 80 km increases northward in summer, according to Quiroz [30]. However, the density at 80 km depends strongly on the thermodynamic state of the troposphere, and it does not follow that the increase northward is necessarily a consequence of the meridional flow.

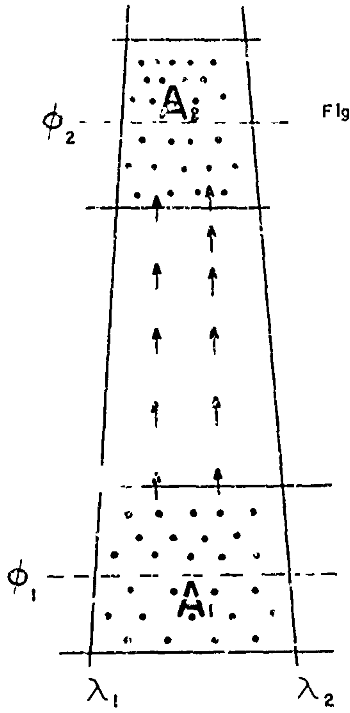

Figure 4. Schematic Illustration of Increase of Particle Concentration Northward

an indefinitely increasing dust concentration at the higher latitudes is not expected. Some diffusion of the particles should be expected as a result of reversals or other changes in the meridional circulation, and in winter, when thermal conditions are relatively unfavorable for the formation of a dust layer, a dispersal of the dust in the vertical is expected, with a possible leakage to the regions underlying and overlying the mesosphere. It has not been our intent to present a complete theory, but rather to suggest a mechanism that could account for an *increased* concentration of dust particles in middle and high latitudes. Under conditions of mesospheric thermal instability, the tendency to accumulation near the mesopause would result in a further increase in particle concentration, thereby creating (other things being equal) the optimum condition for NOC occurrence.

Details of the theory are not yet worked out. A careful examination of the meridional circulation as a function of latitude and longitude is required. If this theory holds, its main practical significance should be that, although some dust near 80 km might be expected at all latitudes, the presence of NOC in specific latitudes could be interpreted as evidence of increased concentrations of dust.

SECTION D – CLIMATOLOGY

Statistics on the distribution of NOC should be based ideally on the results of continuous series of observations made by trained observers under similar viewing conditions, and over a sufficiently large area that visual detection is not entirely prohibited by tropospheric cloud cover. Viewing conditions are a function of the duration of the period when the sun's angle below the horizon is approximately in the range, $6° < \gamma < 18°$. In this range of solar depression, the light contrast over the distant horizon is most favorable for the visual detection of NOC.

The length of the favorable viewing period depends on latitude, and on the sun's declination $(-23\,1/2° < \delta < +23\,1/2°)$, thus on the time of year. At latitudes 50° to 60°N the viewing period is from 2 to more than 5 hours, being at a maximum near midsummer. (At sufficiently high latitudes, the sun in midsummer does not descend more than 6° below the horizon, and the lack of adequate light contrast precludes the observation of NOC at and near the summer solstice.) In low altitudes the viewing period is significantly reduced, but NOC could still be seen if they were present. At 30°N, for example, approximately 2 hours of viewing time are available each night throughout the year. The absence of reports of NOC in low latitudes, even in systematic observational series such as those reported by Astapovich [3], for Ashkabad, 1942-49 (38°N) and Alma-Ata, 1955-57 (44°N), supports the view that NOC are a phenomenon of middle and high latitudes, only.[5]

Chronology.

Before reviewing details of the latitudinal distribution of NOC it will be useful to examine their chronology since 1885. For this purpose we have assembled numerical data for individual years, based on the published compilations listed below. Soviet IGY results are also shown, but these will be discussed subsequently.

SOURCE	PERIOD OF REPORTS	AREA
Vestine [39]	1885-1933	mainly central and west Europe
Astapovich [2]	1885-1944	U. S. S. R.
Spangenberg [35]	1932-1941	unidentified, presumably central Europe
Paton [27] [28]	1939-1963	Abernathy, Scotland
Ludlam [22]	1954-1955	Torsta, Sweden
Witt [42]	1956	Torsta and Stockholm
Pavlova [29]	1957-1958	U. S. S. R.
Fogle [7], [8], Hanson [13], and Lindley [21]	1956-1963	North America

Table 1 gives, by months and years, the number of nights, *n*, on which NOC were observed, according to each of the above sources. Within each source, multiple reports on the same night were counted as one observation. Noctilucent clouds typically have a horizontal extent of several hundred kilometers, so that nearby stations normally sight the same cloud. If a sufficiently wide longitudinal interval is sampled various statistics can be derived, but in this section only data on "nights when NOC occurred" are considered.

Inspection of the individual compilations of Vestine, Astapovich, etc., shows significant disagreement in the annual total number of occurrences. In 1921-1930, for example, Vestine shows no occurrences, whereas Astapovich shows a total of 85. Conversely, in the period 1886-1895, Vestine gives 121, whereas Astapovich shows only 5. Some of the variation might be explained by differences in geographical areas sampled, but it seems likely that the major variation is due to differences in the number of observers available in these areas.

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[5] Noctilucent clouds observed in southern Arizona at about latitude 33°N, in June and November 1963, are considered to have been due to the launching of rockets from the Pacific Missile Range (Meinel and Meinel, [24]), and are excluded from consideration in this report.

Table 1. Number of Nights, *n*, Noctilucent Cloud Observed, 1885-1963, According to Various Authorities, with Representative Annual Totals (column A) and Three-Year Running Means (column B)

Year	Source	May	Jun	Jul	Aug	Total	A	B
1885	Ves		7	13		20	20	20
	Ast		1			>1		
1886	Ves	1	14	14	2	31	31	30
	Ast					1		
1887	Ves		18	20		38	38	28
	Ast			1		1		
1888	Ves		9	7		16	16	21
	Ast			1		1		
1889	Ves		3	3	3	9	9	12
	Ast					0		
1890	Ves	1	2	8		11	11	9
	Ast		2			2		
1891	Ves		4	3		7	7	7
	Ast					0		
1892	Ves	1		1	2	4	4	5
	Ast					0		
1893	Ves		2	1		3	3	3
	Ast					0		
1894	Ves		1	1		2	2	2
	Ast					0		
1895	Ves					0	0	1
	Ast					0		
1896	Ves					0	0	1
	Ast					0		
1897	Ves					0	2	2
	Ast		2			2		
1898	Ves					0	3	5
	Ast		1	1	1	3		
1899	Ves		1			>1	9	5
	Ast		2	7		9		
1900	Ves					0	2	4
	Ast			2		2		

Table 1. Number of Nights, n, Noctilucent Cloud Observed, 1885-1963, According to Various Authorities, with Representative Annual Totals (column A) and Three-Year Running Means (column B) (cont.)

Year	Source	May	Jun	Jul	Aug	Total	A	B
1901	Ves					0	0	<1
	Ast					0		
1902	Ves					0	0	>0
	Ast					0		
1903	Ves			1		1	1	<1
	Ast					0		
1904	Ves					0	1	>1
	Ast			1		1		
1905	Ves					0	2	>1
	Ast		2			2		
1906	Ves			1		1	1	1
	Ast					1		
1907	Ves					0	0	4
	Ast					0		
1908	Ves	1		4		5	12	5
	Ast		3*	9		12		
1909	Ves			1		1	2	5
	Ast	1		1		2		
1910	Ves		1	1		2	2	8
	Ast		1			2		
1911	Ves		5	15		20	20	8
	Ast		2			2		
1912	Ves					0	>1	7
	Ast					>1		
1913	Ves					0	>1	2
	Ast					>1		
1914	Ves		1	2		3	3	1
	Ast		1	1		2		
1915	Ves					0	0	1
	Ast					0		
1916	Ves				1	1	1	>0
	Ast					0		

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* NOC seen by 63 observers on June 30, 1908, night of Tunguskiĭ (Great Siberian) meteorite.

Table 1. Number of Nights, n, Noctilucent Cloud Observed, 1885-1963, According to Various Authorities, with representative Annual Totals (column A) and Three-Year Running Means (column B) (cont.)

Year	Source	May	Jun	Jul	Aug	Total	A	B
1917	Ves					0	0	1
	Ast					0		
1918	Ves					0	2	1
	Ast		1	1		2		
1919	Ves					0	0	2
	Ast					0		
1920	Ves		1			1	3	>2
	Ast			3		3		
1921	Ves					0	4	4
	Ast			4		4		
1922	Ves					0	4	4
	Ast		1	3		4		
1923	Ves					0	4	3
	Ast			3		4		
1924	Ves					0	1	8
	Ast		1			1		
1925	Ves					0	21	14
	Ast	5	13	3		21		

Year	Source	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total	A	B
1926	Ves									0	21	16
	Ast		1		7	10	2	1		21		
1927	Ves									0	5	10
	Ast				2	3				5		
1928	Ves									0	5	9
	Ast				3	2				5		
1929	Ves									0	18	8
	Ast				6	7	3	2		18		
1930	Ves									0	2	8
	Ast				1	1				2		
1931	Ves									0	4	5
	Ast				1	3				4		
1932	Ves					6	1			7	10	8
	Ast				4	6				10		
	Spa									4		

Table 1. Number of Nights, *n*, Noctilucent Cloud Observed, 1885-1963, According to Various Authorities, with Representative Annual Totals (column A) and Three-Year Running Means (column B) (cont.)

Year	Source	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total	A	B
1933	Ves					2	1			3	11	10
	Ast				3	3	1			7		
	Spa									11		
1934	Ast			1	1	4	2			8	10	10
	Spa									10		
1935	Ast					9				9	9	15
	Spa									5		
1936	Ast				7	17	1			25	25	21
	Spa									4		
1937	Ast			1	11	11	5			28	28	22
	Spa									2		
1938	Ast			2	5	4	2			13	13	16
	Spa									1		
1939	Ast				4	2				6	6	10
	Spa									0		
	Pat					1				1		
1940	Ast				3	8	1			12	12	7
	Spa									1		
	Pat				1					1		
1941	Ast					4				4	4	6
	Spa									4		
	Pat					2				2		
1942	Ast				1					1	1	2
	Pat									0		
1943	Ast									0	2	1
	Pat					2				2		
1944	Ast					1				1	1	2
	Pat									0		
1945	Pat				1					1	2	2
1946	Pat					1				1	2	2
1947	Pat					1				1	2	2
1948	Pat					1				1	2	3
1949	Pat					3				3	6	5

Table 1. Number of Nights, *n*, Noctilucent Cloud Observed, 1885-1963, According to Various Authorities, with Representative Annual Totals (column A) and Three-Year Running Means (column B) (cont.)

Year	Source	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total	A	B
1950	Pat				1	2	1			4	8	6
1951	Pat				2					2	4	5
1952	Pat						1			1	2	3
1953	Pat					1				1	2	4
1954	Pat					1				1		
	Lud					3	1			4	8	7
1955	Pat				1	2				3		
	Lud					4	2			6	12	10
1956	Pat					1				1		
	Witt					3	4			7	10	
	Fog				3					3		
1957	Pat					1	1			2		
	Pav				4	18	8	12	2	44		
	Lin					1				1		
	Fog						1			1		
1958	Pat			1						1		
	Pav	6	9	9	13	22	18	11		88		
	Fog				1		1			2		
1959	Pat			1	4	10				15		
1960	Pat			1	7	8	1			17		
1961	Pat				3	7				10		
	Fog					1				1		
	Han							1		1		
1962	Pat				1	3				4		
	Fog			1			4			5		
1963	Pat				1	7				8		
	Fog			1	2	13	8	1		25		

Note: **See text for explanation of column A. In 1956, although data from 2 Swedish stations were available, the entry in column A is simply twice the number of occurrences at one station, Torsta, to maintain consistency with data for 1954-55.**

In order to obtain data which would be as representative as possible of the total number of nights with NOC without regard for geographical area, the largest number reported in each year was entered in column A of Table 1, for years through 1944. In 1945-1955 data based on observations from only one station are represented in each of the sources (Paton, Ludlam). Examination of data for two stations in 1956, Torsta and Stockholm, and for the large Soviet network of stations in 1957-58, shows that the probability of sighting NOC on a given night increases by a factor of almost 2 when the number of stations is increased from 1 to 2 (provided the stations are not situated too close to each other), and increases by a factor of 2 or more when several stations are added. On this basis the one-station data for 1945-1956 were doubled to obtain approximations of the true frequencies in these years. To eliminate further irregularities in the data believed to be due to sampling errors, 3-year running means were obtained (column B). These have been plotted in Figure 5.

The results through 1956 (Table 1 and Figure 5) indicate that the annual number of nights of observed NOC ranges from one or none to 30 or more. A comparison with the IGY network results suggests that the earlier data, based primarily on reports in the literature, underestimate the true frequency by a factor of 2 to 3. Thus, if a sufficiently large area is sampled, it is estimated that the true annual total should range from a few occurrences to perhaps as many as one hundred. The highest probability of occurrences is in the summer months, June, July and August. In each of these months, it is estimated that NOC should occur on about 5 or 10% of the nights in a year of very low cloud activity and on roughly 50% of the nights in a year of high activity.

Although the data in this figure tend to underestimate the true frequencies, the interannual pattern suggested seems real. A cycle with period approximately 12 years is suggested. When compared with the "11-year" sunspot cycle, some similarities and some differences become evident. A physical relationship is not at all improbable, since solar-induced variations in the density and temperature of the atmosphere near 80 km could well have an important effect on incoming meteors and on the subsequent redistribution of meteoric dust particles.

Latitudinal and Seasonal Distribution

A preliminary indication of the distribution of NOC is given in Table 2a as a function of latitude and time of year. These data are based on a compilation made by Gromov [12] from observations in western USSR during 1885-1956. The figures in Table 2a represent the total number of reports, *r*, of NOC (in 5-degree bands of latitude centered on the specified latitudes), and as such may be expected to exceed the number of nights, *n*, with NOC. Gromov reduced his data further by introducing coefficients to account for errors expected from variable duration of viewing period and variable cloud cover. The practice of applying a cloudiness coefficient to such heteorogeneous data as those forming the basis of Table 2a seems questionable. We have gone only so far as to adjust the data to account for the variable duration of the viewing period. This has been done by multiplying the values in Table 2a by a grid of values, each given by the reciprocal of the ratio of the local duration to the maximum possible duration. The latter is aproximately 7 hours, occurs near the summer solstice at 55°N and at some time away from the summer solstice at higher latitudes. As discussed here, the viewing time is the sum of the before- and after-midnight periods of solar depression, $6° < \gamma < 18°$, corresponding to the time of navigational and astronautical twilight, conventionally defined. The adjusted data are shown in Table 2b. A comparison of the two tables shows that the character of the distribution is only slightly affected. In either case the maximum frequency is associated with latitudes 55° or 60°N and July is the month of maximum occurrence.

Since the IGY (1957-1958) important details not suggested by the earlier data have emerged. Observations have been made in North America and elsewhere. The results of the Soviet IGY program are of particular value.

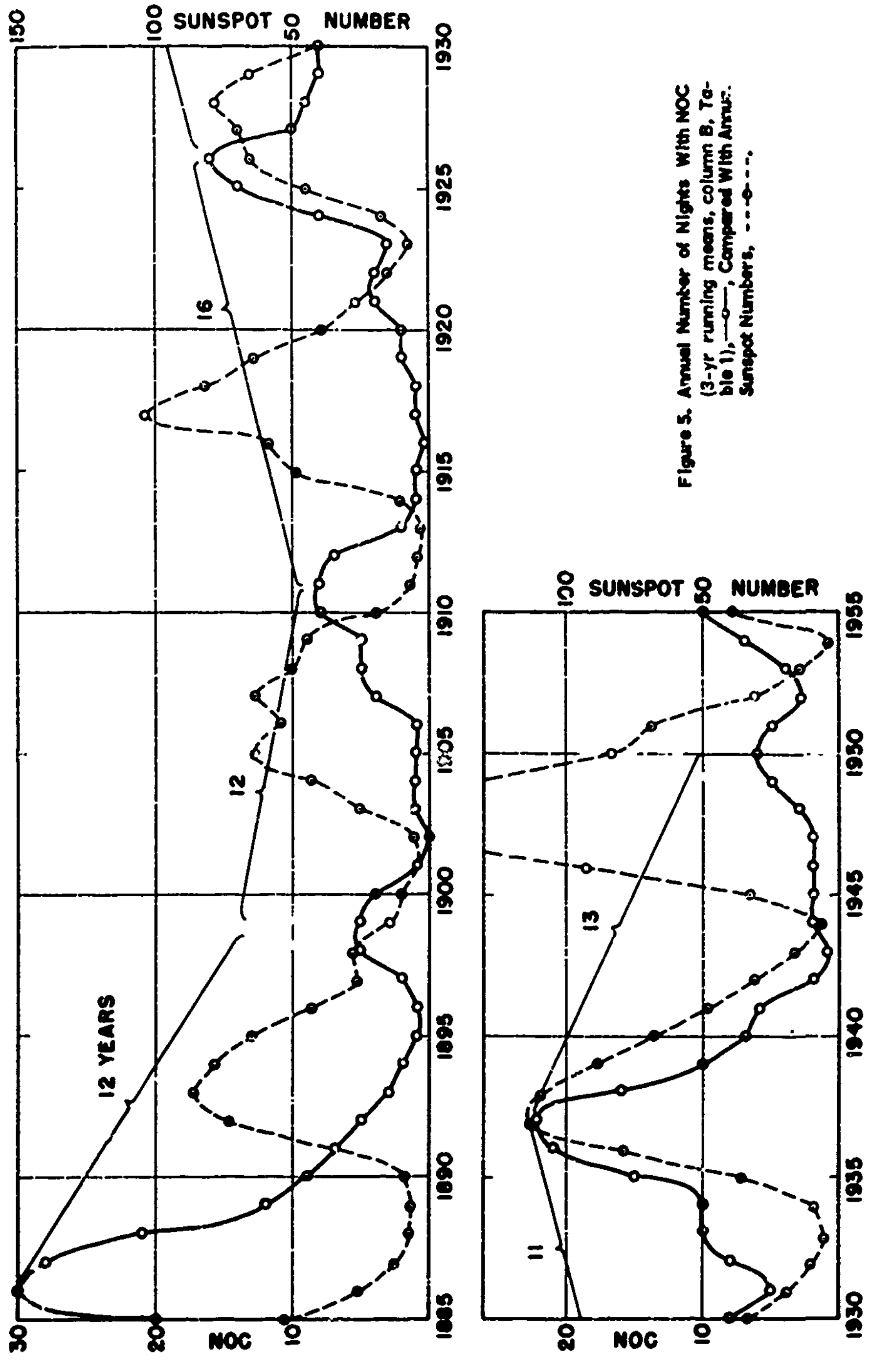

Figure 5. Annual Number of Nights With NOC (3-yr running means, column B, Table 1), —o—, Compared With Annual Sunspot Numbers, - - -o- - -.

Table 2a. Total Number of Reports of NOC, 1885-1956, by 5-Degree Latitude Zones*, According to Data of Gromov [12].

Lat.	Apr	May	Jun	Jul	Aug	Sep	Oct	Total	(%)
45°N	0	0	0	1	1	0	0	2	< 1
50°	0	0	10	15	0	1	0	26	7
55°	0	7	83	130	6	2	1	229	62
60°	2	1	15	75	18	1	0	112	30
Total	2	8	108	221	25	4	1	369	100
(%)	< 1	2	29	60	7	1	< 1	100	

Table 2b. Total Number of Reports of NOC, 1885-1956, by 5-Degree Latitude Zones*, Corrected for Duration of Viewing Period

Lat.	Apr	May	Jun	Jul	Aug	Sep	Oct	Total	(%)
45°N	0	0	0	2	3	0	0	5	< 1
50°	0	0	11	20	0	3	0	34	6
55°	0	8	108	169	10	5	3	303	51
60°	3	2	60	158	23	2	0	248	42
Total	3	10	179	349	36	10	3	590	100
(%)	< 1	2	30	59	6	2	< 1	100	

*Zones centered on indicated latitudes.

In the USSR a network of 220 stations was established for the purpose of obtaining continuous, systematic observations of NOC. Observers were instructed to scan the twilight segment of the night sky every 15 minutes, during the periods of navigational and astronomical twilight ($6^\circ < \gamma < 18^\circ$) and during a short time before and after. Occurrences were recorded along with data on their brightness and on the general sky condition and, in particular, the sky condition in the twilight segment of the sky. Reliable data were actually received from only 79 stations in 1957 and from 201 stations in 1958. Some stations did not report consistently; some stations did not begin observing until 1958. A major difficulty was experienced in regard to the recording of weak, poorly defined NOC; recognition is difficult, even for trained observers in some cases, and the reliability of statistics derived from observations of weak NOC is low.

A catalog of the observations considered reliable has been published by Pavlova [29]. Only data from stations which recorded NOC (76) are given. These stations cover latitudes 47° to 80°N and longitudes 23° to 169°E. Salient features of the seasonal and latitudinal distribution based on these data are depicted in Figure 6 and Tables 3, 4. The statistics refer to either *r*, the number of reports of NOC, regardless of cloud duration, or *R*, the total number of 15-minute periods in which NOC was observed. For comparison, Table 3 gives the monthly number of nights, *n*, of NOC (reports from more than one station reporting counted as one observation) versus *r*.

In about 40% of the observations only one station from the entire network reported NOC. In the remaining cases, 2 to 6 stations made sightings. This is somewhat a surprising result, for even allowing for human observing deficiencies and allowing for the influences of cloud cover, one might have expected visual sightings from larger numbers of stations. In the cases of multiple sightings, the reporting stations were in some cases near to each other (up to several hundred kilometers), and in other cases they were separated by vast distances of the order of several thousand kilometers. In the latter cases, the absence of sightings from intermediate stations suggests that different formations separated by large "clear" areas were present.

Tables 2a and 4 (*r*) describe the same parameter, the number of reports of NOC, the former table based on data for 1885-1956, and the latter based on data for 1958, when a relatively systematic multi-station program was in effect. For convenience, the monthly and latitudinal totals, expressed as percentages, are repeated below (Table 5).

Table 3. Number of Nights (*n*) and Number of Reports (*r*) of NOC, USSR, 1957-58

Year		Mar	Apr	May	June	Jul	Aug	Sep	Oct	Total
1957	*n*				4	18	8	12	2	44
	r				7	28	10	13	2	60
1958	*n*	6	9	9	13	22	18	11	0	88
	r	7	11	11	23	41	32	11	0	136

Table 5. Comparative Data for *r* (Percent Frequency)

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
1885-1956	**0**	**<1**	**2**	**29**	**60**	**7**	**4**	**0**
1958	**5**	**8**	**8**	**17**	**30**	**24**	**8**	**0**
	45°	**50°**	**55°**	**60°**	**65°**	**70°**		
1885-1956	**<1**	**7**	**62**	**30**	**0**	**0**		
1958	**1**	**13**	**41**	**35**	**10**	**<1**		

Table 4. Number of Reports of Occurrences of NOC (*r*) and Number of 15-Minute Periods NOC Reported (*R*), USSR, 1958 Only

	r								*R*							
	45°	50°	55°	60°	65°	70°	Total	(%)	45°	50°	55°	60°	65°	70°	Total	(%)
Mar	0	0	4	2	1	0	7	5	0	0	16	10	2	0	28	3
Apr	1	5	0	4	1	0	11	8	3	17	0	45	1	0	66	7
May	0	2	5	3	1	0	11	8	0	10	30	15	3	0	58	6
Jun	0	1	16	4	2	0	23	17	0	3	149	16	12	0	180	19
Jul	0	3	21	16	1	0	41	30	0	20	208	99	13	0	340	36
Aug	0	5	5	16	6	0	32	24	0	16	23	137	49	0	225	24
Sep	1	2	4	2	1	1	11	8	4	6	7	19	6	3	45	5
Oct	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0
Total	2	17	56	47	13	1	136	100	7	72	433	341	86	3	942	100
(%)	1	13	41	35	10	<1	100		<1	8	46	36	9	<1	100	

*There were, however, 2 occurrences in October 1957. Also, occurrences at Bukhta Tiksi (80° 20'N) on 18 Sep 58 and 11 Oct 57 are not reflected in this table.

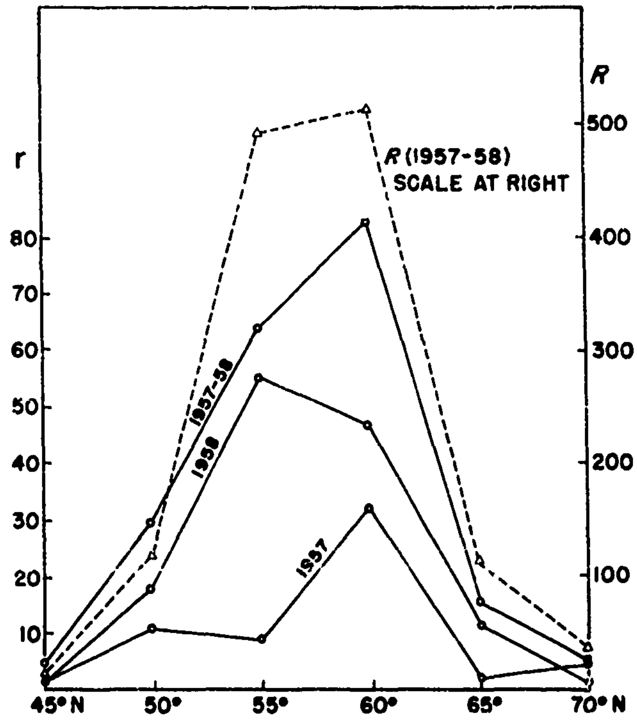

Figure 6. Number of Reports of Occurrences of NOC (*r*) and Number of 15-Minute Periods NOC Reported (*R*), USSR, 1957-58.
Adapted From Pavlova [29].

The distribution for 1958, with respect to both time of year and latitude, shows much less peakedness than the distribution from 1885-1956. A bias in the older data, which were derived largely from reports in the literature, is clearly indicated. Both distributions, however, agree with respect to the time and latitude of maximum frequency, July and 55°N. One interesting difference is the shift to higher frequencies in the later months of the year and in higher latitudes, revealed by the more reliable data for 1958.

The later sample shows that the period when NOC are visible is longer than previously assumed. The earliest NOC recorded was on 13 March 1958, at Kustanai (53°10'N, 63°35'E), the latest on 11 October 1957, at Bukhta Tiksi (80°20' N, 52°55' E). In latitudes to the north of 60°, the maximum frequency indicated by the IGY data is some time after the summer solstice. The data for high latitudes are particularly difficult to evaluate because of greater tropospheric cloud cover and because in midsummer the sun does not sink enough below the horizon to permit the observation of NOC. The absence of a double maximum, which would be expected in view of a double maximum in length of viewing period, is surprising. It is not likely explained by the seasonal cloud cover regime in these latitudes; climatological charts of mean cloud cover in the evening hours (Air Weather Service, [1]), do not show any significant difference in spring and fall. However, it is possible that a close examination of the actual cloud conditions in 1958 would reveal a significant cloud effect.

The true northward extent of NOC is not known. In the Soviet area they have been observed to 80°N (Bukhta Tiksi), in Alaska to 67° (Fogle, [7]), in Sweden to 63° (Ludlam, [22]), and in the Arctic Ocean to 76°, from

Ice Island ARLIS II on 13 September 61 (Hanson, [13]). The clouds are commonly observed at a few degrees above the distant northern horizon, so that they may actually extend to several degrees above the latitude of the observer.

Time and Duration of NOC.

The dependence of observations of NOC on the solar depression angle is clearly demonstrated in Table 6, which shows that 92% of the USSR sightings were made when the sun ranged from 5.6 to 17.5 degrees below the horizon, 10 to 11 degrees being the most favorable angle. This finding is in good agreement with Ludlam's [22] results based on Swedish observations in 1954-55. The actual times corresponding to the given range of solar depression can be calculated by formula (see Ludlam) or they can be easily approximated by finding the times of nautical and astronomical twilight in standard ephemeris tables.

According to the Soviet IGY observations, the mean duration of NOC is 1 hour 38 minutes. Monthly mean durations, in hours and minutes, are given below:

Mar	Apr	May	Jun	Jul	Aug	Sep
1.00	1.30	1.05	1.57	2.04	1.45	1.02

The maximum duration was 5 hours 30 minutes (Suntar Khayata, 62°38' N); the cloud was of exceptional brightness and lasted from 2123 hours to 0238 hours, the night of 4-5 July 1957. Minimum duration was 15 minutes. The clouds tended to be more frequent after midnight rather than before; a consistent relationship is not evident. Of 25 displays observed in North America during 1963, Fogle [8] reports that 17 were seen before midnight.

Table 6. Number of 15-Minute Periods NOC Observed *(R)* as Function of Solar Depression, 1957-58

Angle (°)	R	(%)
1.5 - 3.5	22	1.7
3.6 - 5.5	32	2.5
5.6 - 7.5	106	8.3
7.6 - 9.5	249	19.5
9.6 -11.5	343	26.8
11.6 - 13.5	265	20.7
13.6 - 15.5	164	12.8
15.6 - 17.5	53	4.1
17.6 - 19.5	36	2.8
19.6 - 21.5	9	0.7
Total	1279	

The preceding discussion refers to periods when the clouds have been *seen*. It is natural to inquire whether the clouds might be seen throughout the day and night, given continuously favorable viewing conditions. The fact that the clouds are seen according to the time of favorable solar depression angle, rather than according to clock time, suggests that clouds present on a given night are present throughout the night, at least. Their presence in daytime would also be expected, unless there were some diurnal factor strong enough to inhibit the concentration of particles near the mesopause. The diurnal density bulge of the atmosphere, which above 300 km is responsible for daytime values of air density which exceed the nighttime values by several factors, could possibly inhibit the influx of meteoric material to NOC altitudes. This effect can be inferred, though imperfectly, in the diurnal curves of radar meteor counts in summer (Figure 2). The means for finding a complete solution to this problem are not yet available; some investigative effort is feasible.

Longitudinal Variations.

An inspection of the detailed observational data for longitudes 23°E to 169°E did not indicate a longitudinal preference for the occurrence of NOC. Evidence of the occurrence of NOC during the same night (Local time) at widely separated longitudes is available, not only from the data under discussion, but also from other sources. For example, on the night of 27 July 57, when two Soviet stations at longitudes 29° and 38°E reported NOC, there were reports also of NOC over south central Alaska, in the vicinity of 150°W. The dearth of reports from the North American area before 1962 suggests that the frequency is lower here than in Eurasia, but no reliable statement can yet be made. A systematic watch was begun at College, Alaska in 1962. A network of observing stations was established in Canada and Alaska in 1963. The number of cloud displays seen increased from 5 in 1962 to 25 in 1963. It is evident that the results of concurrent observing programs in several areas of the world are needed before the question of longitudinal differences can be adequately resolved.

The Height of Noctilucent Clouds.

As with so many meteorological phenomena, there has been an unfortunate tendency to ascribe a specific value, usually 81 or 82 km, to the altitude at which NOC occurs. Khvostikov ([19a], and earlier reports), in fact, speaks of the "constancy" of the cloud height, employing this notion to support the condensation hypothesis for the origin of the clouds.

The following data give an idea of the range of observed heights:

SOURCE	HEIGHT ESTIMATES
Jesse [19]	79-90 km, mean height 82.1 km; based on data from 24 photographic plates 1889-91.
Ludlam [22]	Mean heights in 3 observations by Störmer in 1932-34: 81.8, 81.1, 82.2 km, determined from numerous individual measurements ranging over 78-85 km.
Paton [27]	84-89 km; based on 28 observations, 1939-58.
Hanson [13]	70 km (?), NOC observed at 76°N on 13 September 1961.

Allowing for possible error in the height determinations, it is reasonable to consider 75 to 90 km as the approximate height range within which the great majority of the observations fall. The mean height of occurrence lies probably between 80 and 85 km and is possibly a function of latitude and solar activity.

Day-to-day variations in the height of the mesopause are suggested in the rocket-grenade temperature data of Nordberg and Smith [26]. In view of the apparent role of the thermal structure with regard to both condensation and dust accumulation (see section B), it is possible that day-to-day variations occur also in the height of the NOC. Atmospheric temperature measurements made simultaneously with height observations of NOC will help to clarify this question. Such measurements have been planned by the National Aeronautics and Space Administration for the summer of 1964.

SECTION E — CLOUD DIMENSIONS AND MOVEMENT

Knowledge of the structure of NOC is necessary in order to make a proper interpretation of available data on cloud movement. NOC structure has been studied intensively by Grishin [11], with the aid of motion pictures, and by Witt [44], who worked with stereoscopically analyzed photographs taken with accurate phototheodolite cameras.

Results of the Soviet IGY network and the more recently established North American network indicate that individual cloud systems may have a horizontal extent of thousands of kilometers.

A well-developed cloud system consists typically of a seemingly continuous diffuse layer punctuated by wave-like formations of at least two scales:

(1) Long waves with lengths 30 to 100 km and amplitudes 2 to 3 km. The crests are readily seen as long, nearly parallel bands stretching over a substantial part of the northern sky.

(2) Smaller "billows" with wave lengths 4 to 10 km and amplitudes about 1/2 to 1 km.

The long waves, which may have their origin in internal gravity waves of the atmosphere (Hines, [17]), are propagated at some angle to the general motion of the cloud system and may even move in an opposite direction. The billows have been observed by Witt to move in the same direction as the cloud system, passing through the crests of the longer waves. He shows that the error introduced by using the motion of the billows for an estimate of the horizontal wind speed may be fairly small.

To estimate the movement of the cloud system, past observers have often tracked a bright area at the crest of the longer waves, favoring especially an exceptionally bright area at the intersection of two nonparallel bands. It is possible that such measurements do not correctly represent the motion of the cloud, in view of the angle of propagation. Moreover, the tracking of bright areas formed at the intersection of two wave groups with different velocities may lead to apparent velocities which grossly over estimate or underestimate the motion of the cloud.

In spite of the shortcomings in past methods of estimating cloud movement, there is a remarkable consistency in the results.

Vestine [39], discussing some early cloud velocity data (1889-94) compiled by Jesse, cites a modal direction from the ENE, with a possible secondary maximum from the west. An average velocity of 67 m/s from the east and a maximum velocity of 177 m/s are mentioned. Vestine's own summarization of data to 1932 likewise shows a maximum number of cases of cloud movement from ENE, and a maximum velocity of approximately 200 m/s, NNE. Paton [27] states that all clouds observed in Scotland, 1939-59, "drifted to the west". Spangenberg [35], considering central European data for 1932-41, indicates movement from E and ENE in 67% of the cases, the cloud speeds averaging less than 100 m/s.

To obtain further details of the movement of NOC, a tabulation was made of velocity data for 1885-1940, using the individual observations published by Astapovich [2] together with data for 1954-55 published by Ludlam [22]. The velocity estimates were made by visual or photographic means and occasionally with the aid of theodolites. Most of the data for 1885-1940 were re-evaluated, or were initially evaluated, by Astapovich himself. Almost all the values pertain to observations in June-August.

The summarization of NOC velocity data is necessarily subjective. Some of the reports give *ranges* of direction and speed, according to the complexity of cloud structure and movement. For the purpose of summarization data were tabulated for a single representative velocity vector, or in a few cases of clearly disparate motions, for two representative vectors. Also, when more than one observation was available for the same night, only one set of representative data was used. As there seemed to be no clear correlation of cloud velocity with hour of the night, the velocities for all observation times were summarized together. The results are shown in Table 7. It will be noted that fewer speed measurements than direction measurements were available; this is reflected in the relative number of cases, *n*, versus *N*, respectively.

These data essentially confirm earlier deductions regarding the movement of NOC. In about 75% of the cases, the clouds moved from directions north through east; ENE is the predominant direction. Movement from any other direction seems possible, although with a strongly reduced probability.

In 73% of the cases speeds were in the range 26-100 m/s. The strongest speeds were from the north and northeast. Maximum cloud speeds reported are 308 m/s and 230 m/s. These values seem unusually high for the height region under consideration, 75 to 90 km. At these heights, maximum winds observed by the rocket grenade technique (Nordberg and Smith,[26]) are of the order of 200 m/s. The cloud speeds cited above were determined with the aid of several photographs, yet it is possible that some feature of the NOC was being tracked whose apparent motion was not representative of the motion of the cloud system nor of the wind. On the other hand, if winds as high as 200 m/s have been observed in relatively short periods of observation, for example, by the rocket grenade technique, it is not too surprising, from a statistical point of view, to note maximum cloud speeds up to 300 m/s from a long period of record.

Table 7. Frequency Distribution of Cloud Velocities, 1885-1940, 1954-55

Direction (from)	*N* (All Speeds)	Direction	No. of Cases, *n*, by Speed Groups (m/s)					
			≤25	26-50	51-75	76-100	101-150	>150
SW	1	SW	1	1				
W	4	W						
NW	5	NW	1	1		2		
N	14	N		3/1	1	2	1	1**
NE	29	NE	1	1	2/2	1/1	1	1*
E	34	E	1	4	2	2		
SE	5	SE		1		1	2	
S	6	S	1	1		1		
Total	98		5	13	7	10	4	2
		(%)	12	32	17	24	10	5

Speed data were less plentiful than direction data, thus $n < N$. Values of *n* preceded by slant line refer to measurements at Torsta, Sweden, 1954-55.

*308 m/s, July 17, 1935, morning.

**230 m/s, Aug. 8-9, 1925, midnight.

A physical explanation of the velocity regime of NOC is beyond the scope of this report. Aside from the possible influence of internal gravity waves, atmospheric tidal oscillations are an important consideration. Evidence is available (e.g., Rosenberg and Edwards, [31]; Lenhard, [20], Greenhow and Neufeld, [10]) of large diurnal variations in the wind. The velocity data examined were predominantly at times between 2000 and 0400 and would tend to homogeneity with respect to the diurnal cycle, but it is clear that any interpretation of the data should be made within the framework of the diurnal regime.

Finally, vertical wind shear may have a significant effect on the cloud movement. Chemical cloud experiments carried out with rockets have revealed layers of strong shear in the lower thermosphere. The following example of NOC movement, taken from Astapovich [2] appears to reflect a vertical wind structure not unlike the pattern revealed in the rocket experiments.

June 20, 1937 Moscow 2330-2430 h.	"Near upper boundary, motion to west; in lower half of cloud, motion to north."

SECTION F – PARTICLE SIZE AND CONCENTRATION

Until recently, only indirect observational evidence existed for estimates of the particle size and concentration in noctilucent clouds. A sample of cloud particles has now been obtained in specially designed rocket experiments carried out in Sweden (Soberman, [34]; Hemenway and Soberman, [15]; Skrivanek and Soberman, [33]), and the results obtained thus far tend to strengthen the validity of the calculations based on indirect evidence. Further experiments with rockets are planned for the summer of 1964.

Before considering the data specifically relating to NOC, it is pertinent to ask whether dust particle counts obtained from satellites and rockets in general might be extrapolated to infer particle concentrations at NOC altitudes, 75-90 km. The majority of the reliable data from rockets are for heights 100 to about 150 km. The data from satellites are for higher altitudes and have been obtained under a variety of observational circumstances, which makes their interpretation especially difficult. Whipple [41] and Dole [5] have suggested that the concentration of particles near the earth should vary inversely as the 1.4 power, or 1.66 power, respectively, of the distance from surface of the earth. According to McCracken and Alexander [23], however, confirmation of a clear dependence of particle concentration on altitude is lacking. The relationships suggested by Whipple and Dole are probably useful for first approximations. However, they do not allow for deviations in particle concentration that might be associated with specific features in the temperature and density structure of the atmosphere, as at the mesopause. Thus, in general, it is considered unrealistic to extrapolate particle concentrations obtained at rocket and satellite altitudes down to the altitudes of noctilucent clouds.

Actual data on NOC particle size and concentration will now be considered. Indirect observational evidence has led to a definition of the expected range in cloud particle radius. From the degree of polarization and color of light from NOC, Ludlam has deduced a particle radius ranging between 10^{-6} and 10^{-5} cm. From detailed polarization measurements on August 10-11, 1958, Witt [43] found a variation in particle radius from 1 to 2.4 $\times 10^{-5}$ cm. Ludlam estimated the particle concentration by (1) using camera exposure times as an inverse measure of the brightness of the clouds; and (2) assuming a proportionality between cloud brightness and the particle scattering of light. Further considerations led to an expression for the particle concentration,

$$n = (2 \times 10^{-6})\, h \pi\, r^2 ,$$

where r is the particle radius and h is the thickness of the cloud layer. The thickness of NOC commonly ranges from less than 2 to more than 4 km. Choosing h equal to 3×10^5 cm, the particle concentration.

$$n \simeq 2 \times 10^{-2}/\text{cm}^3 \qquad \text{if } r = 10^{-5}\text{cm}$$

$$n \simeq 2/\text{cm}^3 \qquad \text{if } r = 10^{-6}\text{ cm}$$

Note that if the particle radius is over- or underestimated by one order of magnitude, the concentration is in error by a factor of 100.

If for a cloud particle we assume a spherical shape and a radius of 10^{-5} cm, the volume of the particle is:

$$(4/3)\pi(10^{-5})^3 \simeq 4 \times 10^{-15}\text{ cm}^3.$$

If we further assume the mass/cm^3 of the material constituting the cloud to be 2.5 grams, the mass of one particle will be

$$(2.5)\ 4 \times 10^{-15} = 10^{-14}\text{ grams.}$$

Then, assuming a particle concentration of $2 \times 10^{-2}/\text{cm}^3$, we have the density contribution at NOC altitudes by NOC,

$$(2 \times 10^{-2}/\text{cm}^3) \times 10^{-14}\text{grams} =$$

$$2 \times 10^{-16}\text{ grams/cm}^3.$$

The average summertime atmospheric density at latitudes 49-75°N (Quiroz, [30]) is 2.3×10^{-8} g/cm^3. In a volume containing NOC, the contribution to the total density by the NOC is approximately $(2 \times 10^{-16})/(2.3 \times 10^{-8}) \simeq 10^{-8}$. Thus it appears that the contribution of the space density of the NOC particles to the total density is extremely small. Since the masses and sizes of the individual particles are very much greater than those of the air molecules, abrasive effects on an aerospace vehicle may still be important.

It is of interest to compare the particle sizes and concentrations deduced in the manner described above with actual samples. As mentioned earlier, rocket experiments conducted in Sweden in 1962 have resulted in some preliminary data. Particle samples were obtained on two successful flights, one of which was in the presence of NOC (August 11). The other flight (August 7) yielded a particle count, per unit area, 2 to 3 orders of magnitude less than the noctilucent sample.

The radius of the particles in the noctilucent sample ranged primarily from 2.5×10^{-6} to 2.5×10^{-5} cm, in remarkably good agreement with the combined range indicated by Ludlam and Witt, 10^{-6} to 2.4×10^{-5}. For $r > 2.5 \times 10^{-6}$, particle counts of 1 to 8×10^6 per square cm of collecting surfaces were obtained. Particles were collected between the altitudes of 75 and 95 km, so a further reduction of the data is needed to approximate the concentration per cubic centimeter. If the concentration is assumed constant with height, n takes on a value of 0.5 to 4.0 particles/cm^3. It is expected, however, that the major contribution would have been in the height domain of the NOC, probably only a few kilometers. Thus, it is expected that the particle concentration in the cloud itself would have been somewhat larger. In any case the observed values of n are near or above the upper boundary deduced by Ludlam's method. Further samples to be obtained in the summer of 1964 should better define the range of particle concentration.

SECTION 6 — SUMMARY

Of the existing concepts of the origin of noctilucent clouds, the concept of interplanetary particles in sufficient concentration to be seen as "cloud" is favored. A mechanism which could explain the necessary accumulation of particles near the mesopause is meridional convergence of particles initially distributed uniformly with latitude.

The temperatures required for condensation near the mesopause have been observed to occur. In a rocket sample of cloud particles, about 10% of the particles had a structure suggesting that the particles had been surrounded by ice. In view of the large proportion of particles not possessing this feature, it is believed that condensation is not necessary for NOC to exist.

Representative data on cloud characteristics are given below. Values for cloud dimensions are based primarily on the work of Witt [44] and Grishin [11].

Heights: 75 to 90 km (about 250,000 to 300,000 ft)

Thickness: <2 to > 4 km

Horizontal extent of cloud system: Up to several thousand kilometers

Wave features: Long waves, wave lengths 30 to 100 km and amplitudes 2 to 3 km; billows, wave lengths 4 to 10 km and amplitudes 1/2 to 1 km

Observational conditions: Most favorable solar depression angle, 6 to 18 degrees (92% of Soviet IGY sightings were made in this range of solar depression). Clouds can be seen with solar depression angle 1 to 22 degrees. Elevation of clouds above horizon, primarily 1 to 15 degrees; but cloud can extend to and beyond zenith. Viewing time (total of period after sunset and before sunrise), increases from about 2 hours each night at 30°N latitude to 2 to 7 hours at 50°N, 2 to 5 hours at 60°N. At the higher latitudes the viewing time depends strongly on time of year, is at a maximum near midsummer.

Frequency of occurrence as function of . . .

Inter-annual behavior: There is an apparent cyclical variation in the annual number of occurrences, with period approximately 12 years. According to pre-IGY data, the annual number of nights with NOC varies from .1 or none in a year of minimum cloud activity to 30 or more in a year of maximum activity. Comparison with IGY results suggests that the earlier data in general underestimate the true frequency by a factor of 2 to 3.

Time of year: Clouds have been seen as early as mid-March, as late as mid-October, (Northern Hemisphere). They are seen most frequently in June, July, and August. In these months, they are seen on about 5% of the nights in a year of low activity, on about 50% of the nights in a year of high activity.

Latitude: Clouds have been seen between latitudes 45° and 80°N. Whether or not the observed frequencies are corrected for duration of viewing period, the frequency of occurrence is highest near 55° and 60°. The general increase northward in tropospheric cloud cover in summer may tend to mask the true frequencies at the higher latitudes.

Longitude. Time of Day: Definitive information is lacking; see appropriate sections of this report.

Cloud movement: The field of motion is complicated by possible effects of internal gravity waves, atmospheric tidal oscillations, and vertical wind shear. Propagation of wave groups may be at some angle to the motion of the cloud. Summarization of past estimates of cloud motion, 1885-1940, indicates that in 75% of the cases, clouds moved from directions north through east, with ENE as modal direction. In 73% of the cases cloud speeds were in the range 26-100 m/s. Maximum cloud speeds reported, 308 and 230 m/s, are subject to further review.

Particle size and concentration: Polarization measurements lead to deduced particle radii in the range 10^{-6} to 2.4×10^{-5} cm (Ludlam, [22]); Witt, [43], and particle concentrations of $2/\text{cm}^3$ to $2 \times 10^{-2}/\text{cm}^3$. These estimates agree well with measurements from rocket sampling of NOC, but tend to underestimate particle concentration.

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