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Noctilucent Clouds Seen from North America

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ABSTRACT. Noctilucent clouds are tenuous ice clouds that form in the upper mesosphere over arctic and subarctic regions in the summer. Observations of the clouds made during 1988 and 1989 by the North American surveillance network NLC CAN AM are presented. Observing took place from 15 May to 15 August, except for arctic sites, which observed from 1 April to 30 April and 15 August to 15 September due to the Midnight Sun. The peak incidence of noctilucent clouds occurred in July during both years.

Both positive and negative sightings, the latter determined by at least two readings under favourable conditions, are plotted on date-latitude graphs.

An apparent northern migration of noctilucent clouds (NLC) with latitude as the season progresses was detected. Although an attempt was made to look for an apparent longitudinal drift, none was found.

A detailed comparison of how NLC have behaved and changed in the past quarter century is examined using the NLC CAN AM data in conjunction with the 1964-65 data presented by Fogle (1966).

Key words: noctilucent clouds, northern migration, longitudinal drift, comparison

RÉSUMÉ. Les nuages noctulescents sont minces nuages de cristaux de glaces qui se forment dans la haute mésosphère, au-dessus des régions arctiques at subarctiques, durant l'été. On présente ici les observations de nuages noctulescents effectuées en 1988 et 1989 par le réseau nord-américain du: North American surveillance network (NLC CAN AM). La périod d'observation fut du 15 mai au 15 août, sauf pour les stations actiques, où à cause du soleil de minuit, elle fut du ler au 30 avril et du 15 août au 15 septembre. Le maximum d'activité des nuages noctulescents apparut en juillet durant les deux années.

Les observations positives et négatives, ces dernières étant déterminées par au moins deux relevés effectués dans de bonnes conditions, sont pointées sur des graphiques de la date en fonction de la latitude.

Un apparent déplacement vers le nord, en latitude, des nuages noctulescents (NNL), fut détecté à mesure que la saison progressait. Par ailleurs, une tentative pour déceler une dérive en longitude fut infructueuse.

Une comparaison detaillée du comportement et des changements des nuages noctulescents au cours du dernier quart de siècle, est analysée en utilsant les données du NLC CAN AM et celles de 1964-1965 présentées par Fogle (1966).

Mots clés: nuages noctulescents, déplacement vers le nord, dérive en longitude, comparaison

КРАТКИЙ ОБЗОР. Серебристые облака представляют собой тонкие ледяные облака, которые формируются летом в верхней мезосфере над арктическими и субарктическими районами. В работе представлены наблюдения серебристых облаков проведённые в 1988 и в 1989 гг. Северо-Американской обзорной сетью СО КАН АМ. Наблюдения проводились с 15 мая по 15 августа за исключением арктических пунктов, где из за белых ночей наблюдения проводились с 1 апреля по 30 апреля и с 15 августа по 15 сентября. Максимальная сфера распространения наблюдалась в июле в обоих годах. И положительные и отрицательные наблюдения представлены на графике с датами и широтами. Отрицательные наблюдения определены по крайней мере двумя показаниями в благоприятных условиях. Была замечена видимая северная миграция серебристых облаков (СО) по отношению к широте с развитием сезона. Несмотря на то, что была сделана попытка обнаружить долготное перемещение, оно не было обнаружено. В конце работы представлено детальное сравнение того, как (СО) двигались и менялись в последней четверти века используя данные СО КАН АМ совместно с данными представлеными Фогл (1966) в 1964-1965 гг.

Ключевые слова: серебристые облака, северная миграция, долготное перемещение, сравнение

INTRODUCTION

Noctilucent clouds (NLC), perhaps the most elusive and least understood cloud formations, evolve over arctic and subarctic areas from May through August. When the sun is around 6° below the observer's horizon these clouds appear (Paton, 1964). The display is usually visible until the sun is around 16° below the horizon, at which point the NLC are no longer illuminated by the sun (Paton, 1964). At a mean height of 82 km (Fogle, 1966), noctilucent clouds are the highest known clouds in our atmosphere, occupying its coldest reaches in the

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upper mesosphere (Gadsden and Schröder, 1989), where summer temperatures drop to 140°K (Turco *et al.*, 1982). NLC are believed to be composed mostly of ice crystals (Fogle, 1966); how the required water vapour reaches such a remote region has been the subject of much inquiry. A computer model by Turco *et al.* (1982) suggests advection of water from lower levels of the atmosphere and subsequent nucleation upon meteoric particles and hydrated ions.

Exacerbating the problems of explaining how an NLC display is formed is the fluctuation of NLC-observing programs. The absence of an ongoing ground-based global effort has perpetuated noctilucent clouds' status as no more than being a little understood manifestation of the atmosphere. Scientists have shown an interest in such observations, which serve to complement existing satellite, rocket, and radar studies in attempts to illuminate the nature of NLC and their effects on us. Consisting of North American amateur enthusiasts in association with staff observing voluntarily at several weather and flight service stations, since 1988 the NLC CAN AM (Noctilucent Cloud Canadian American) network has undertaken a concerted synoptic monitoring of the mysterious phenomenon of noctilucent clouds (Fig. 1). Participants, whose locations are shown in Figure 2, conduct nocturnal sky checks within the official viewing period of 15 May to 15 August to determine the presence or absence of NLC from their locations. Climatological data collected from all observers at each season's conclusion allows evaluation of active and inactive nights and the real extent of NLC displays.

OBSERVATIONS

Shown in Figures 3A and B are nights when the NLC CAN AM network recorded both positive and negative sightings of NLC during the network's observing seasons for 1988 and 1989 respectively. The sites are listed in order of decreasing latitude, with Cambridge Bay and Cape Parry having different observing periods due to their high latitudes. Each square denotes a particular night, with certain squares further divided into top left triangles and lower right triangles, representing readings made before and after local midnight respectively. The absence of any symbol denotes one or more of several prohibitive variables, such as the lack of observation, tropospheric cloudiness, and insufficiently or incorrectly completed report forms. Some of the more northerly sites — namely, Cambridge Bay, Cape Parry, Fairbanks, Ft. Reliance, Ft. Simpson, and Watson Lake — on several nights encompassing the summer solstice were unable to observe or had severely limited observing periods due to bright twilight conditions. As these stations, Fairbanks excluded, conducted hourly readings, the most extremely attenuated nights when viewing was possible possessed only one hourly reading. This lone observation may have been either an evening or morning one, depending

FIG. 1. Noctilucent cloud display as seen in the northeast sky from Fairbanks, Alaska, on 7 August 1989, 1028UT. Photograph taken with 35 mm lens, f/2, 15 s exposure, on Kodachrome 64 daylight professional film. Photo by Robert E. Fischer.

on which side of local midnight the reading fell upon. For amateur observers, readings made from supplementary sites within a 100 km radius of their principal sites listed are included in those sites' data.

Figures 3A and B, representing observations conducted during entire nights, can be modified to indicate those nights when actual NLC displays likely occurred, along with those that were probably free from NLC. Governing this evaluation, as previously mentioned, is the sun's situation below the observer's horizon, the solar depression angle (SDA). Those values that permit NLC visibility are between 6 and 16° below the horizon (Paton, 1964). Figures 4A-D, dividing the network into western and (far less representative) eastern components bestriding 90°W longitude, delete nights in 1988 and 1989 when all positive readings from a site had corresponding SDAs > 16.0° and/or < 6.0°. Negative nights are determined on the basis of a minimum of two clear sky readings, both within the 6.0-16.0 SDA range, and one on either side of local midnight, to ensure both evening and morning visibility intervals are surveyed. Exceptions are those aforementioned northern stations where only one reading was taken on certain nights — in these cases, the single observation is used for negative night determinations. Sites are positioned as a function of latitude, as depicted by Christie (1967).

RESULTS

Of special note are two positive sightings of noctilucent clouds, one each at the southern and northern fringe zones of visibility. From Oakville, Ontario (latitude 43.3°N), the phenomenon was reported on the night of 15 July 1988. This observation, if valid, may be of key significance, as NLC are rarely, if at all, seen from below the 45th parallel. According to a reliable survey by Fogle (1966), one of the most recent surveys from which we can derive comparisons, the most southerly North American sighting before 1965 was from Montreal, Quebec (latitude 45.5°N), in 1964. From the same study, the most northerly positive report had been from Arlis II Ice Island (latitude 76.3°N), in 1961. This limit was also approached in 1988, when observers at the Atmospheric Environment Service station at Cape Parry, Northwest Territories (latitude 70.2°N) recorded NLC on the night of 10 September.

ANALYSIS

Latitudinal Drift

A poorly understood property of NLC is the apparent migration towards higher latitudes as the season progresses. Fogle (1966) had commented on this apparent migration, making a reference to peak activity occurring earlier at the lower latitudes. Contributing to the progression are a number of processes. The accepted processes are: 1) The improvement of viewing conditions in the north as the NLC season advances and perpetual daylight changes to twilight, enabling NLC to be detected (Fogle and Haurwitz, 1966), and 2) the temperature profile of the upper mesosphere, where the ambient temperatures actually increase as summer moves forward (Stroud *et al.*, 1960), resulting in an environment gradually less conducive to NLC development. Water vapour concentrations by either chemical, ionic, or meteorological processes also play a (less understood) role (Gadsden and Schröder, 1989).

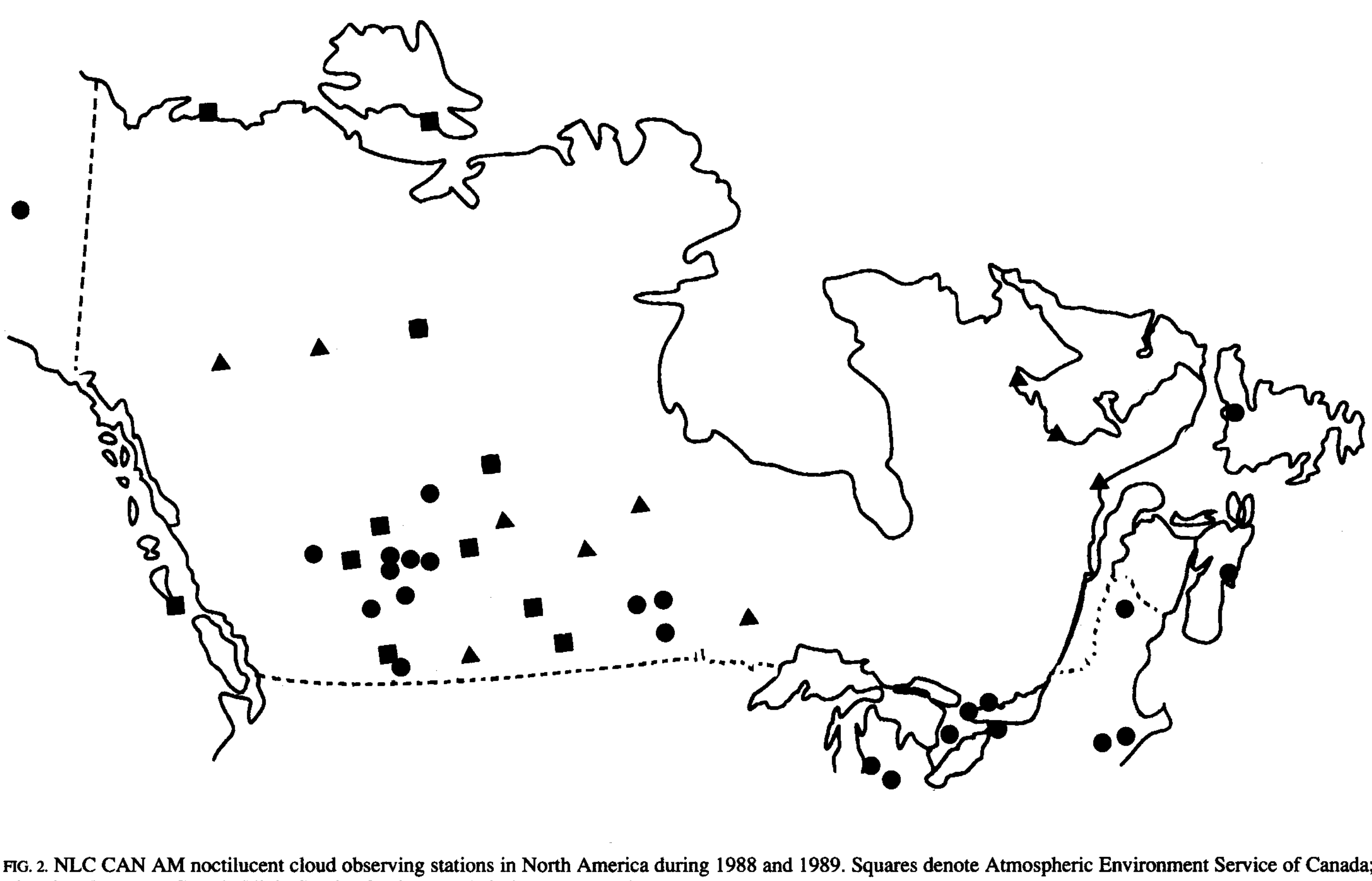


FIG. 2. NLC CAN AM noctilucent cloud observing stations in North America during 1988 and 1989. Squares denote Atmospheric Environment Service of Canada; triangles, Transport Canada Flight Service Stations; and circles, amateur observers.

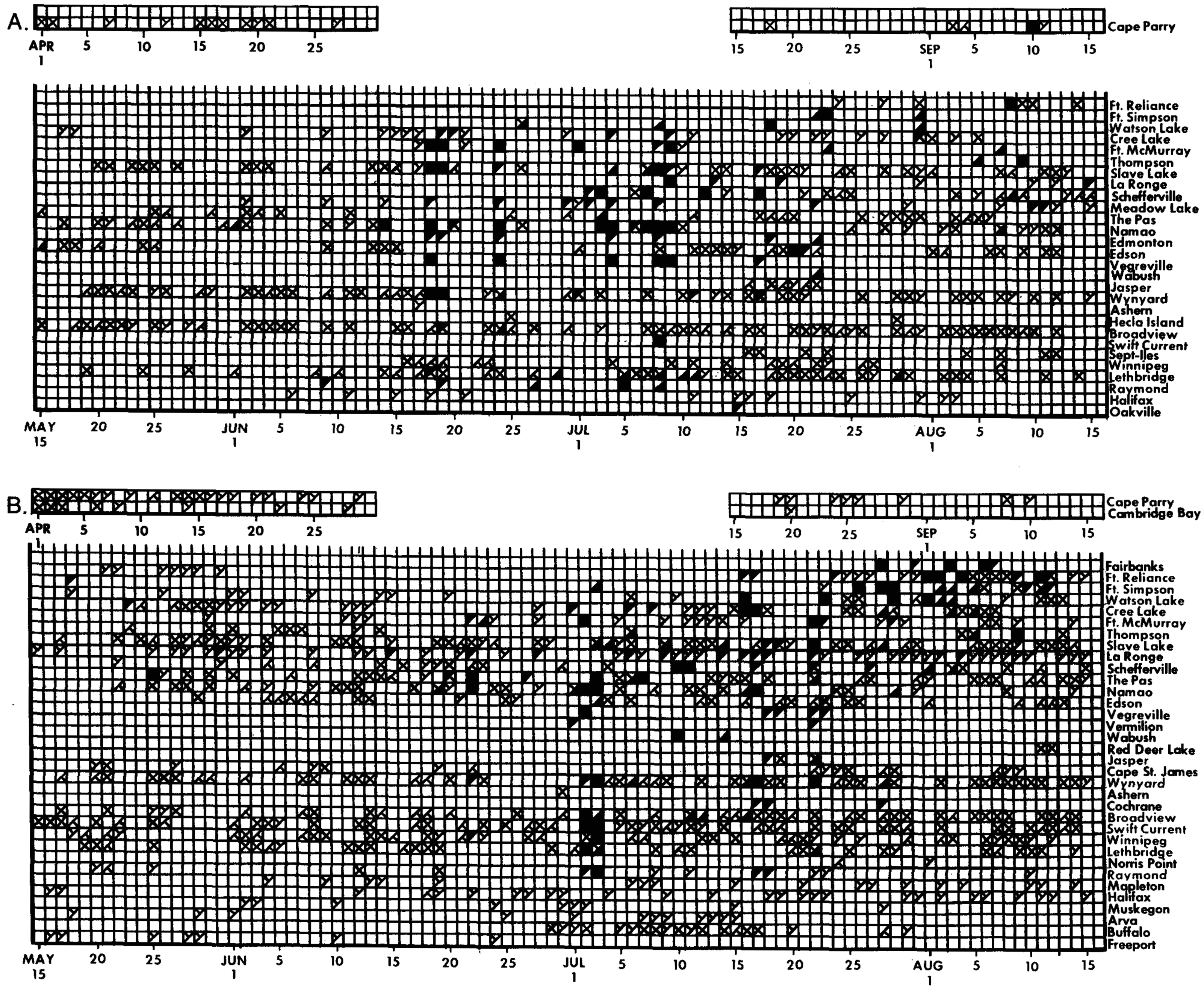
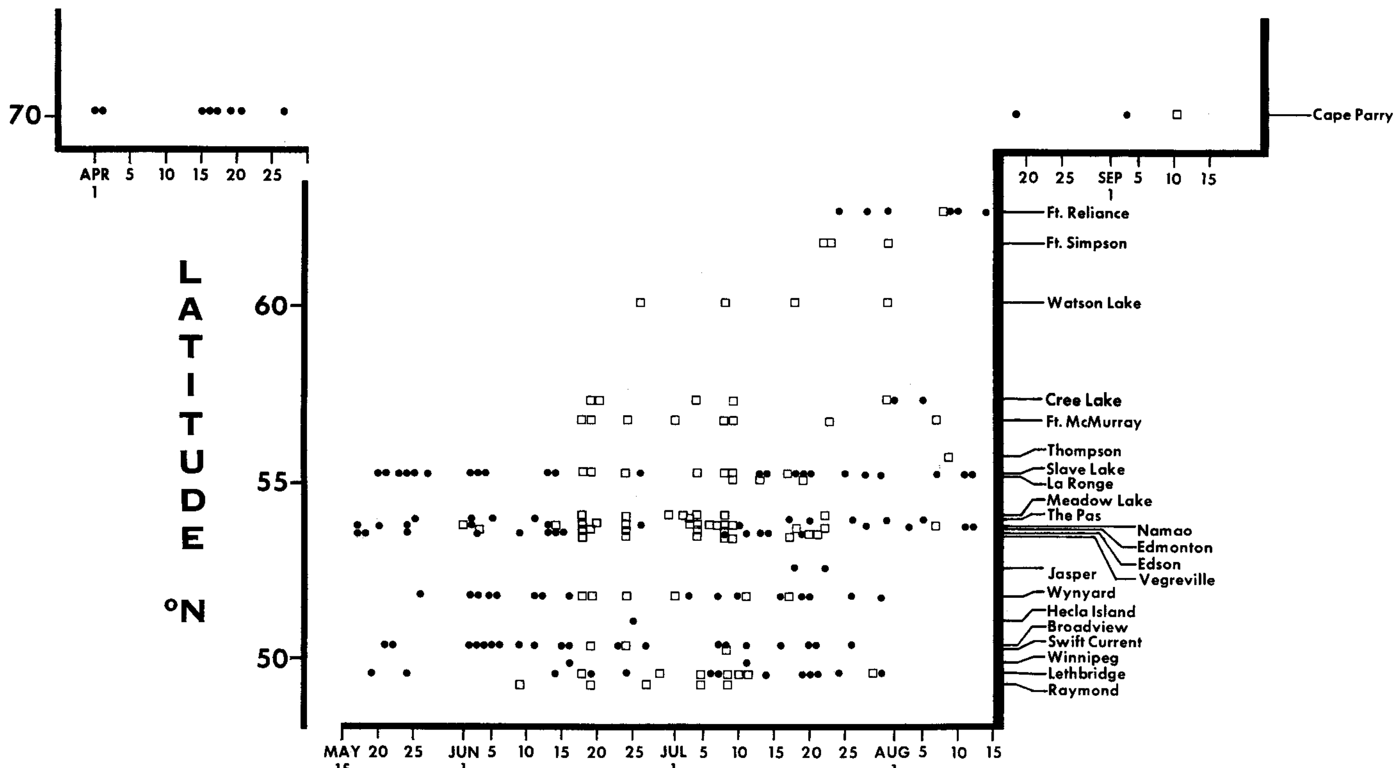
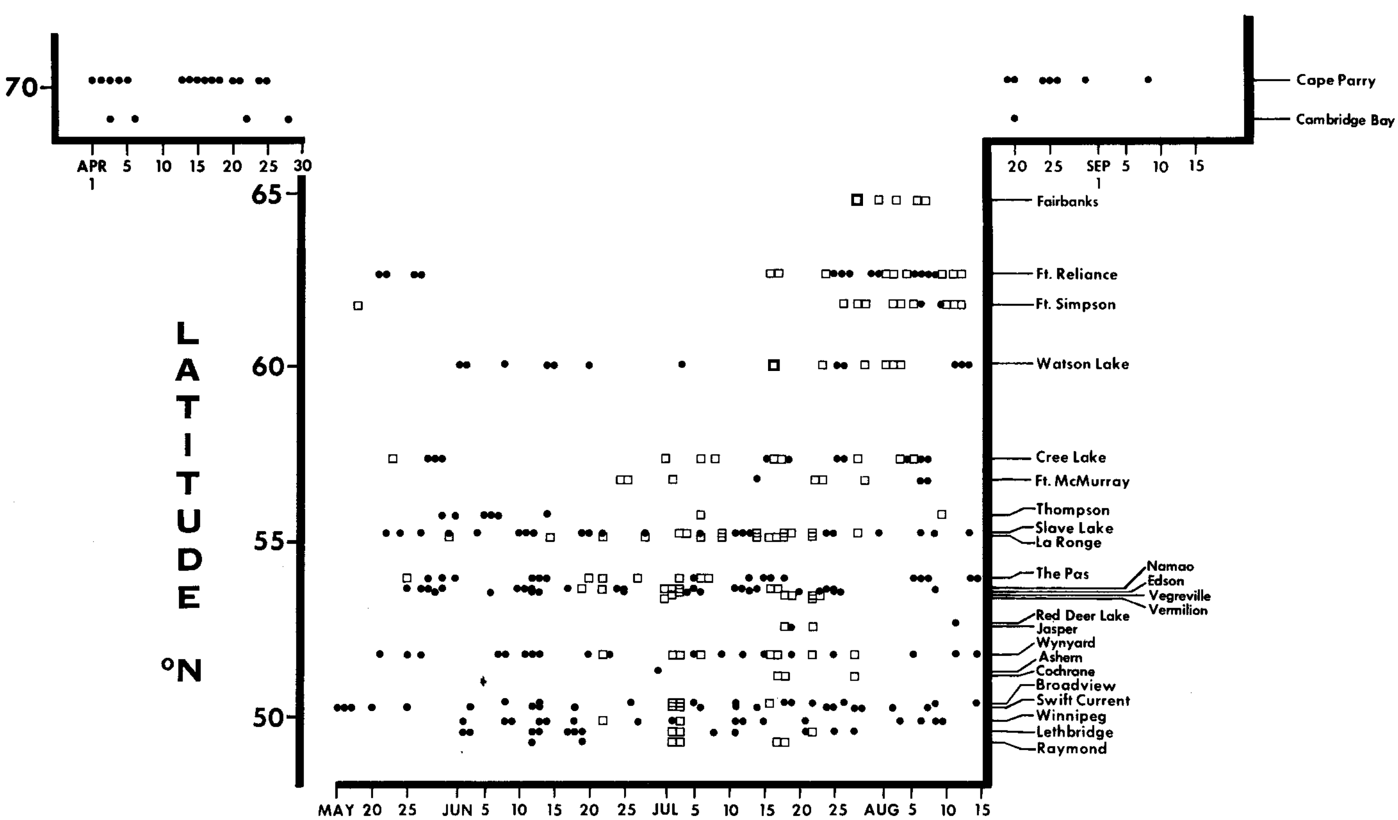


FIG. 3. Positive and negative sightings of noctilucent clouds over North America in (A) 1988 and (B) 1989. Bisected triangles indicate positive sightings and filled triangles are negative observations. *The y-axis gives the site location and the x-axis indicates the date (night of) the observation.*

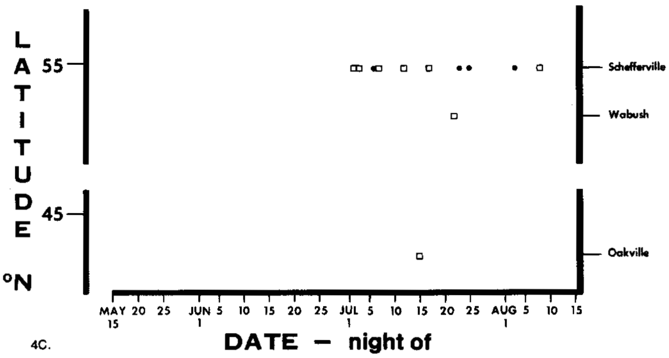


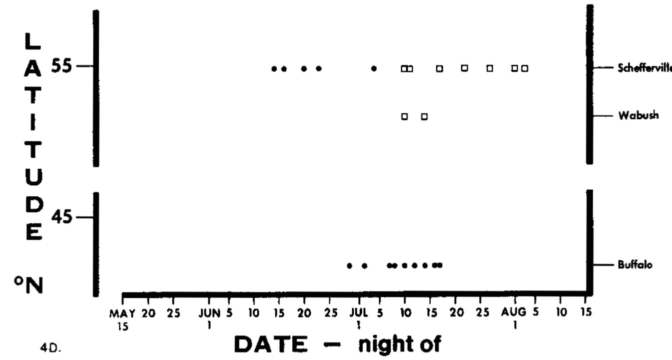
4A.



4B.

FIG. 4. Positive and negative sightings of NLC when required number of determining readings had corresponding solar depression angles between 6.0 and 16.0°, in (A) western North America, 1988, (B) western North America, 1989, (C) eastern North America, 1988, and (D) eastern North America, 1989. Open squares denote positive observations and closed circles are negative reports.





Observing Figures 3 and 4, the trend of NLC occurrence is shown to be drifting northward at a reasonably fast rate after summer solstice. In the lower latitudes, NLC are common in June and early July but are rare by late July, when their presence becomes more common at higher latitudes. This trend can be seen solely from the NLC CAN AM data of 1988 as reported by Zalcik and Lohvinenko (1989). Fogle (1966) and the NLC CAN AM network have shown the apparent increase of NLC activity to be close to, but after, summer solstice. From the above figures, one may be inclined to believe such a positive northern progression does exist. However one must be cautious about what is perceived. The removal of observing sites that did not observe every night of the season, for example, must be considered. Even when this is done (Fig. 5), there is still an indication of a true northern progression of NLC.

The problem becomes one of showing that this is a real effect and not an illusion. To do this we have employed a statistical model that yields unbiased estimators to a possible best-fitted curve. The statistical model known as least squares fitting was employed, as it gave unbiased, and thus unspurious, results with the data available. The basic principle behind least squares fitting consists of minimizing the overall discrepancy in the observed data compared with the predicted data (Bhattacharyya and Johnson, 1977). Defined as D, the general form becomes

$$D = (O-C)^2 \tag{1}$$

Using the observing sites found in Figure 6, we then determined the *arithmetic mean date* for all positive NLC displays and plotted it against latitude. Here we define May 01 = 121 for 1989 and 122 for 1988.

We then computed a least squares best-fit polynomial curve to the data provided by the NLC CAN AM network. The results of the 1989 data yield the following two best equations, based on polynomial equations up to degree N–1 (=9).

$$y = 87.9 + 1.98x (s^2 = 16.8) \tag{2a}$$

$$y = 928 - 28.2x + 0.268x^2 \ (s^2 = 18.6) \tag{2b}$$

Using the variance (s^2) to be a true indicator of which equation is a better fit to the data, one may be inclined to believe the linear relationship is the better. Statistically, however, there only exists a 50% chance either equation will give the best fit.

Using both the 1988 and 1989 data collected by the NLC CAN AM network, an improvement in determining which equation is the best fit becomes evident.

$$y = 36.3 + 2.87x \ (s^2 = 84.6) \tag{3a}$$

$$y = 611 - 17.0x + 0.171x^2 (s^2 = 50.3) \tag{3b}$$

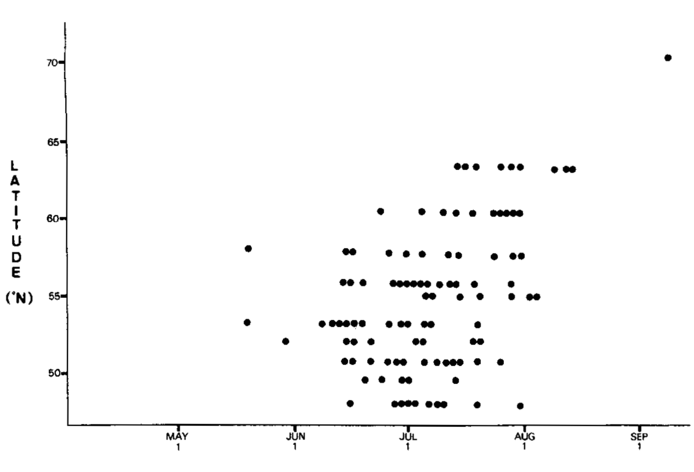


FIG. 5. Scatter diagram showing the distribution of positive NLC displays for 1988 and 1989. The observing stations used are only those that observed during every night of the observing season.

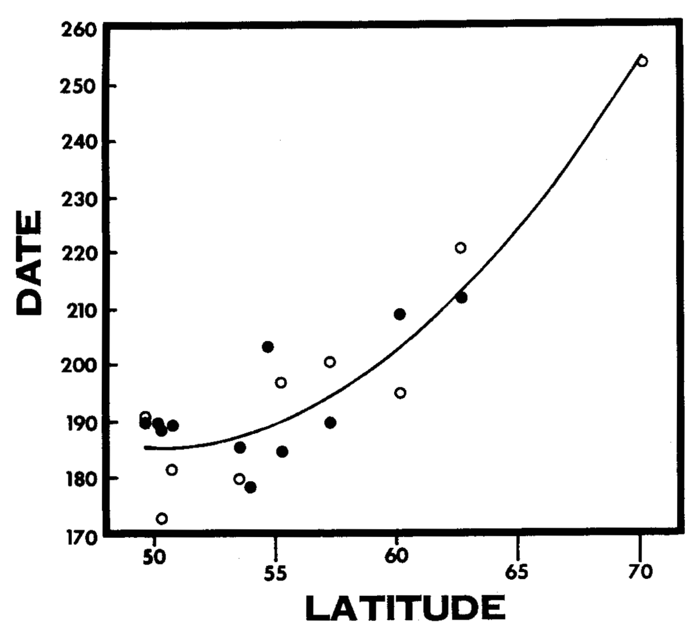


FIG. 6. Arithmetic mean dates computed from the data used to create Figure 5. A best-fit curve shows the apparent positive migration of NLC with respect to the aging of the season.

Again computing the possible equations up to degree N–1 (=19); the two best-fitting curves turn out to be a linear equation and a quadratic equation. Using both the 1988 and 1989 data, there appears to be a significant improvement for the quadratic case. In fact there is a 63% chance the quadratic case is the better of the two equations.

It is our belief that if there exists a real relationship between noctilucent clouds and the apparent seasonal drift with respect to latitude, equation 3b best represents this relationship. In considering the errors that accompany least squares fitting, our equation becomes

$$y = 611(\pm 5) - 17.0(\pm 0.1)x + 0.171(\pm 0.001)x^2 \qquad (3c)$$

These results show there is a dynamic positive acceleration in the NLC latitudinal progression (Fig. 6) as the NLC season progresses. This acceleration of 0.34 days/degree^2 might suggest some form of physical behaviour that might be proportional to the progression in the increasing solar depression angle or upper atmospheric heating during the summer. Whatever the outcome of studies regarding the physical properties and behaviour behind noctilucent clouds, these accounts of the apparent northern migration of NLC due to an apparent positive acceleration of NLC must be considered when dealing with the modeling of noctilucent clouds and the atmosphere.

Longitudinal Drift

It has been suggested by professional noctilucent cloud experts in the United Kingdom (R.J. Livesey, pers. comm. 1989) that there is a real difference between the NLC found in North America and those found in the United Kingdom. The general reasoning behind this belief hinges on the Canadian Rocky Mountain chain, which is believed to propagate turbulence into the upper atmosphere to perhaps influence the general appearance and behaviour of noctilucent clouds. The Rocky Mountains may have an influence on the appearance of NLC, but do they affect the migration of NLC? In our study of longitudinal migration of NLC we concentrate on six observing stations positioned around 55°N latitude and spanning a longitude between 60 and 120°W longitude. In Figure 7, one can see the dates when NLC were visible during the 1988 and 1989 observing seasons. Fitting a best-fit curve to the data, Figure 8 shows the curve to be a linear relationship with a slope of nearly zero.

In our study, the computed straight line relationship has an $r^2 = 0.302$. This tells us that about 30% of variability in y is explained by the linear relationship. Seeing that r^2 is small, we can only conclude that a straight line does not give a good fit to the data. There are two possible reasons for such a small value: 1) There is little relationship among the variables; thus the scatter diagram fails to exhibit a pattern. In this case any regression model other than the linear model is not likely to give a more reasonable fit (Bhattacharyya and Johnson, 1977). 2) There may exist a dominant nonlinear relationship to the scatter diagram.

In the case of (2), we have looked at other possible least square curves up to degree 10 and have found the overall discrepancy to increase rapidly. This implies that a relationship of any kind is highly unlikely. We believe that (1) is the best explanation to fit our data. Thus the evidence obtained from the statistical study indicates that there exists insufficient evidence for a migration of NLC with respect to longitude.

The late arithmetic mean value of Schefferville is somewhat puzzling and may hold some weight. This value may be due to a lack of positive observations mixed with the random nature of NLC appearance, which seems to be more evident in this case. However even if this implies some kind of physical relationship between the Rocky Mountains and NLC, we do have a significant gap between the longitudes of 65 and 100°, which would likely be detrimental to any further analysis.

Temporal Trends

In the mid-1960s an extensive NLC program was carried out by Fogle (1966). Using his data collected during clear nights, we can compare his results with ours. We concentrate our study on our most reliable and most observed latitude, 55°N. Using the criteria he had established, we then determine the relative frequencies for each ten-night interval from 1-10 June (interval 1) up to and including 1-10 August (interval 7). We then normalize his and our data from the 55° latitude zone and present it in histogram form (Fig. 9). Normalizing the data results in the area under our curve and Fogle's (1966) curve to be equal to one.

What is quickly noticed is the symmetry about the fourth ten-night interval, 1-10 July. This symmetry is less pronounced in the 1964-65 data and appears to be shifted, lying between the fourth and fifth ten-night interval. In general the 1964-65 and 1988-89 data appear to be similar in shape and probability. There are exceptions to this observation. For example, in the case of 1-10 June, it would appear as if in 1964-65 the frequency of NLC was higher than in 1988-89, while in the case of 21-30 June the opposite was true.

From a quantitative viewpoint the mean and variance of the 1964-65 and 1988-89 data appear to be very similar. Using the mean and variance to be indicators of how much activity changed in the past, we have found we cannot dispute any changes in the NLC distribution. It would appear the mean ten-night interval would be 1-10 July, with a standard deviation of ±16 days. Thus 68.3% of the NLC observations collected will fall between a ten-night interval of 4.0±1.6.

We therefore conclude the general form of the distribution of NLC for a latitude of 55° has not changed between 1964-65 and 1988-89. This does not necessarily mean that NLC activity has increased or decreased. To determine how active NLC have been in the past compared to now, we compute for 1988-89, and again for the 55° latitude zone, the number of nights with positive observations divided by the total number of nights in each ten-night period. We then compare the raw probabilities with the data presented by Fogle (1966) for the same latitude. Figure 10 shows that the 1988-89 data is consistently higher in probability, except for the first ten-night interval, than is the case of the 1964-65 data. Assuming the method of analysis was the one applied by Fogle, one could expect the data to render a good comparison between the 1964-65 and 1988-89 data. With this assumption, one can see there has apparently been an increase in NLC activity compared with the 1964-65 data. Gadsden (1982), from global observations, has also noticed an intriguing trend of increasing size and frequency of displays. Among those who addressed this have been Thomas *et al.* (1989), who have attributed this observation to increasing levels of methane, one of the greenhouse gases. However, it must be noted that other methods of NLC frequency analysis we investigated reveal much different results. For example, when NLC clear sky frequency was determined for each site, with the average of all sites' frequencies subsequently calculated for each interval, an overall *decrease* in activity was apparent in the 1988-89 data.

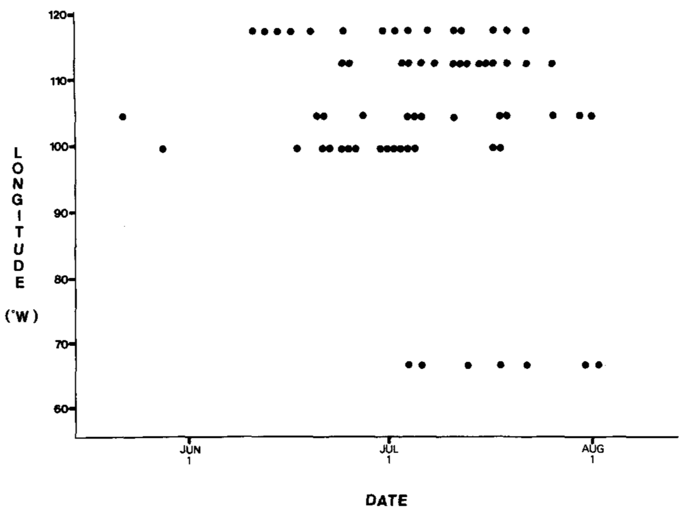


FIG. 7. Scatter diagram showing the distribution of positive NLC sightings for 1988 and 1989 restricted to a latitude of around 55°N. The observing stations used are only those that observed every night of the season.

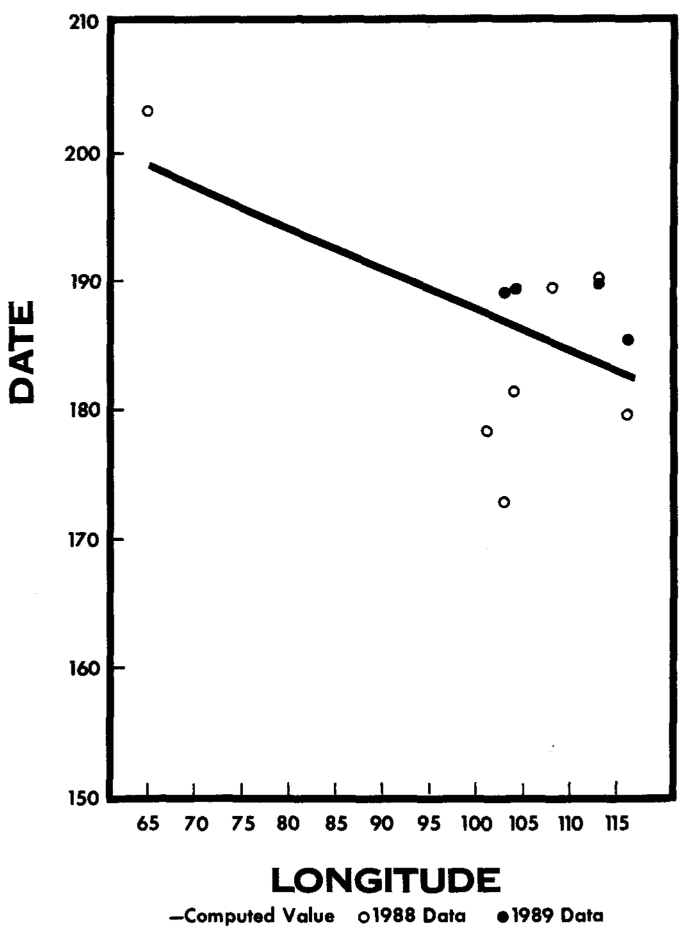


FIG. 8. Arithmetic mean dates computed from the data used to create Figure 7. A best-fit curve attempts to show the apparent negative migration of NLC with respect to longitude. Since the line given by the equation: $y = 220(\pm 7) - 0.32(\pm 0.16)x$ only explains about 30% of the variability in the data, it is unlikely that this is a true representation.

CONCLUSION

NLC CAN AM's 1988 and 1989 observations reveal a typical, yet nonetheless interesting, profile of noctilucent cloud climatological behaviour. Activity begins modestly in late May with small, localized displays, usually seen from latitudes 55-60°N. By late June, both frequency and size of exhibitions increase, with cloud fields occasionally visible over wide areas. Incidence peaks in July, when most nights experience NLC formation over some area of the continent. At least one or two displays reach proportions enabling them to be seen over much of the longitudinal breadth of North America (examples: 22 July 1988 and 1989). A few exhibitions, like those on 8 July 1988 and 3 July 1989, evolve southward enough to allow visibility from latitudes of the upper 40s. By late July, a northerly recession of cloud fields becomes evident. This process continues into August, with displays by then becoming much less frequent in all but those northern areas, poleward from about the 60th parallel, just emerging from their encounter with perpetual bright twilight. Even from this higher latitude zone, the incidence decreases rapidly until the NLC season essentially concludes by September. The northerly migration curiously is not reciprocated in spring, and far northern observers must wait until season's end to see their first NLC display.

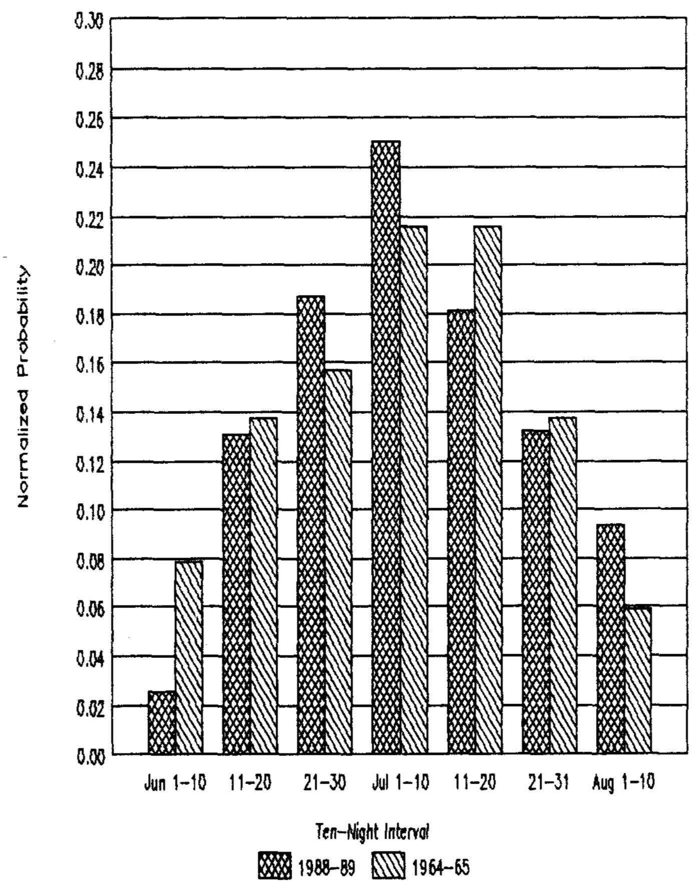


FIG. 9. A normalized distribution of Figure 10 is given. The data show a more symmetrical distribution to the 1988-89 season as compared to the 1964-65 season.

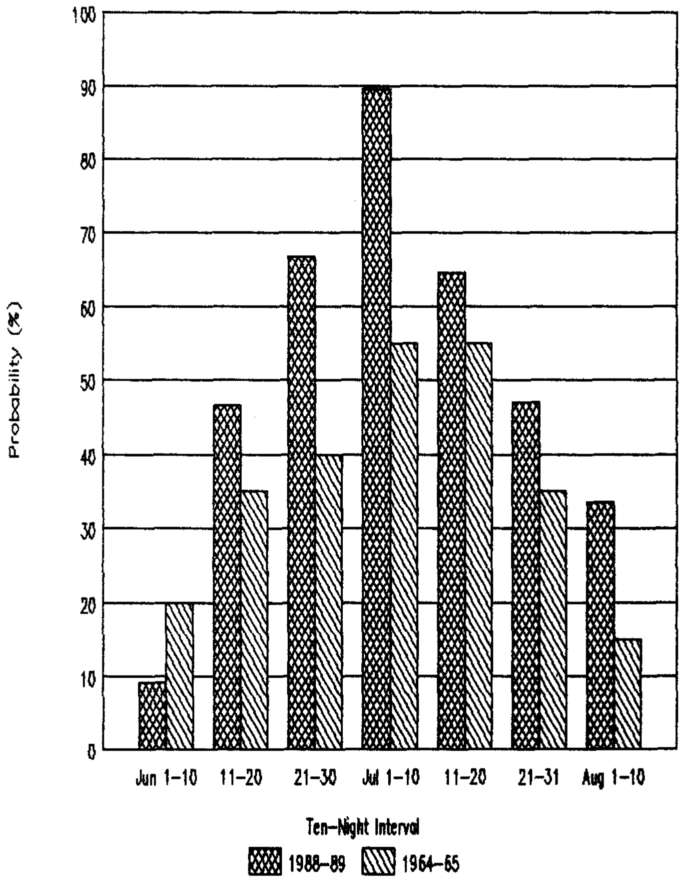


FIG. 10. A comparison of the 1988-89 NLC CAN AM data with the 1964-65 data obtained by Fogle (1966). The histogram shows a significant increase in NLC activity between 21-30 June and 1-10 July. However a significant overall increase does seem unlikely.

There does appear to exist a real possibility of a latitudinal migration of NLC with respect to the aging of the NLC season. If this is true, we have estimated an acceleration in NLC of around 0.34 days/degree^2. However, we have no evidence of a longitudinal migration of NLC with respect to the NLC season. The suggestion of the Rocky Mountain chain influencing the general behaviour and appearance of NLC cannot be disputed with our data; however the lack of evidence for longitudinal variations would seem to weaken this point of view, unless longitudinal variations are improbable or are difficult to detect.

ACKNOWLEDGEMENTS

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APPENDIX

Network participants in 1988 and 1989 were: Atmospheric Environment Service of Canada Stations — Broadview, SK; Cambridge Bay, NWT; Cape Parry, NWT; Cape St. James, BC; Cree Lake, SK; Edson, AB; Fort Reliance, NWT; Lethbridge, AB ; Meadow Lake, SK; Slave Lake, AB; Wynyard, SK (Terry Hitchings and Ron Thompson, contract staff). Transport Canada Flight Service Stations — Fort Simpson, NWT; La Ronge, SK; Schefferville, PQ; Sept-Îles, PQ; Sioux Lookout, ON; Swift Current, SK (Brian and Terri O'Hara, contract staff); The Pas, MB; Thompson, MB; Wabush, NF; Watson Lake, YT.

Individuals were: Michael Boschat, Halifax, NS; Peter Brown, Fort McMurray and Red Deer Lake, AB; David Dawson, Broad Brook, CT; Robert Fischer, Fairbanks, AK; Susan French, Scotia, NY; L. Geelan, Cochrane, AB; Helen Hawes, Fort McMurray, AB; Robert Howell, Fort McMurray, AB; Lucian Kemble, Cochrane, AB; Dale Johnson, Muskegon, MI; Alister Ling, Edmonton, AB, and Toronto, ON; Todd Lohvinenko, Ashern, Hecla Island, and Winnipeg, MB; Wayne Madea, Mapleton, ME; Cheryl Matsugi, Raymond, AB; Steve McKinnon, Oakville, ON; Adrienne Morris, Buffalo, NY; John Rousom, Arva, ON; Art and Joan Seabury, Jr., Norris Point, NF; Don Thacker, Vegreville, AB; Oscar Van Dongen, Vermilion, AB; Karren Webb, Freeport, MI; Mark Zalcik, Jasper, Namao, and Red Deer Lake, AB.

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