Published by Elsevier

Journal of Atmospheric and Solar-Terrestrial Physics, 70, 1460-1472, 2008.

Ground-based observations of noctilucent clouds with a northern hemisphere network of automatic digital cameras

P. Dalin[a,b,*], N. Pertsev[c], A. Zadorozhny[d], M. Connors[e], I. Schofield[e], I. Shelton[e], M. Zalcik[f], T. McEwan[g], I. McEachran[g], S. Frandsen[h], O. Hansen[i], H. Andersen[i], V. Sukhodoev[c], V. Perminov[c], V. Romejko[j]

[a]*Swedish Institute of Space Physics, Box 812, SE-981 28 Kiruna, Sweden.*

[b]*Space Research Institute, RAS, Profsouznaya st. 84/32, Moscow, 117997, Russia.*

[c]*A. M. Obukhov Institute of Atmospheric Physics, RAS, Pyzhevskiy per., 3, Moscow, 119017, Russia.*

[d]*Novosibirsk State University, Pirogova st. 2, Novosibirsk, 630090, Russia.*

[e]*Athabasca University Geophysical Observatory, T9S 3A3 Athabasca, Alberta, Canada.*

[f]*NLC CAN AM Network, #7 14130 80 Street, Edmonton, AB, T5C 1L6, Canada.*

[g]*NLC NET, 14 Kersland Road, Glengarnock, Ayrshire, KA14 3BA, Scotland, UK.*

[h]*University of Aarhus, Ny Munkegade, Bygn. 1520, DK-8000 Aarhus C, Denmark.*

[i]*The Danish Association for NLC Research, Lyngvej 36, Kolvrå, DK-7470 Karup J., Denmark.*

[j]*The Moscow Association for NLC Research, Kosygina st. 17, 119334, Moscow, Russia.*

*Corresponding author: Peter Dalin, E-mail: pdalin@irf.se; Fax: +46-980-79050

Keywords: Noctilucent clouds, tides and planetary waves, mesospheric dynamics

Abstract

For the first time we present an analysis of observations of noctilucent clouds obtained with a network of automatic digital cameras located at opposite sides of the northern hemisphere. The advantage of this network is that cameras are located along the same latitude circle producing comparable measurements. We find there is an indication of the 2-day planetary wave propagation influencing the occurrence frequency, geographical distribution and brightness variations of noctilucent clouds. The 5-day planetary wave has much less effect on noctilucent clouds than that of the 2-day wave, at least for the summers of 2006 and 2007. At the same time bright noctilucent clouds tend to occur every successive night during short periods of 3-5 nights.

1. Introduction

Noctilucent clouds (NLCs) are the highest clouds in the Earth's atmosphere, observed close to the mesopause in the 80-90 km altitude range. These clouds are a beautiful night-time optical phenomenon occurring during the summer months at mid- and high latitudes. NLCs consist of water ice particles of 30-100 nm in radius that scatter sunlight and thus NLCs are readily seen against the dark twilight arc from May until September (Gadsden and Schröder, 1989).

Although many aspects of the NLC climatology and microphysics of ice particles are well studied, there are still many unanswered questions in the field of NLC research. In particular, what is the geographical distribution of NLCs around the globe and which physical processes control such a distribution. A number of theoretical studies (e.g., Berger and Lübken, 2006) as well as satellite data (DeLand et al., 2003) demonstrate that NLCs (or more exactly, polar mesospheric clouds, PMCs) cover the entire polar mesopause region during summer time. At the same time, some "patches" of PMCs (similar to icebergs from a continent) extend to mid-latitudes and become visible from the Earth's surface as NLCs. But it is poorly understood so far what characteristic sizes of such patches are and which processes are responsible for their formation.

Recent success has been achieved in considering the influence of planetary waves on NLC occurrence over the Northern Hemisphere. Planetary waves disturb the summer mesosphere temperature (Espy and Witt, 1996) to such a degree that a strong correlation exists between the probability of NLC appearance and the combined effect of stationary, 16-day and 5-day planetary waves (Kirkwood and Stebel, 2003). The 5-day period in NLCs was detected using ground-based observations (Gadsden, 1985; Sugiyama et al., 1996; Kirkwood and Stebel, 2003). The signatures of the 5-day planetary wave were also observed in PMCs from satellite data (Merkel et al., 2003). Carbary et al. (2003) demonstrated the geographical distribution of PMCs and found that horizontal scales of PMCs were more than 100 km. Dalin et al. (2006a) found, based on a large set of data, that the longitudinal extent of NLC patches are less than 800 km along a 60° latitude circle.

In the present paper, based on high quality data, we investigate the dynamical variability of NLCs around the globe.

2. Data source

Since 2006 four automatic digital cameras have been operating during summer time (May 25 – August 15) to register NLCs. The cameras are in the Moscow region, Lobnya, Russia (56°N00'; 37°E29'), Lund, Sweden (55°N43'; 13°E13'), Port Glasgow, Scotland (55°N56'; 04°W41') and Athabasca University Geophysical Observatory (AUGO), Athabasca, Canada (54°N44'; 113°W19'). In 2007 the NLC camera in Lund was replaced by a digital camera located in Aarhus, Denmark (56°N10'; 10°E12'), and a new camera was installed in Novosibirsk, Russia (54°N52'; 83°E06'). Note that the NLC cameras in Moscow and Lund have operated since summer 2004. Thus, in the summer of 2007 five NLC cameras were in operation located along the same latitude circle (Fig. 1). Such geographical camera locations provide comparable NLC observations (due to equal twilight illumination conditions and because of equal physical conditions in the mesopause since temperature, vertical and meridional winds are latitude dependent) and provide us with the possibility to study NLC inhomogeneities on continental scales, as well as gravity wave and planetary wave activity. Each camera operates with the same program: from 22:00 to 05:00 LT at the beginning (May 25–June 9) and end of the NLC season (July 26–August 15), taking images every 3 minutes, and from 23:00 to 04:00 LT during high NLC season (June 10–July 25), taking images every 1 minute. The total number of observational nights for each season is 83. The field of view of cameras located in Moscow, Aarhus and Port Glasgow is 42x55°, whereas the cameras in Novosibirsk and Athabasca have a wide-field objective of 59x78°. There are two supplementary digital cameras located in Moscow region (Zvenigorod and Krasnogorsk), separated from the first one by 50 and 20 km, respectively. At present the NLC cameras in Canada and Denmark are connected to Internet providing real time data; images from other cameras are processed after the end of the summer.

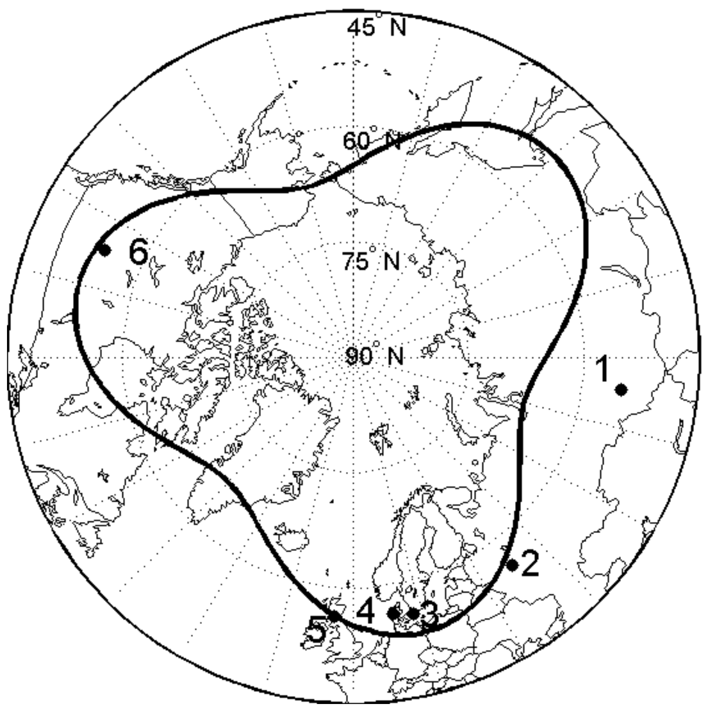


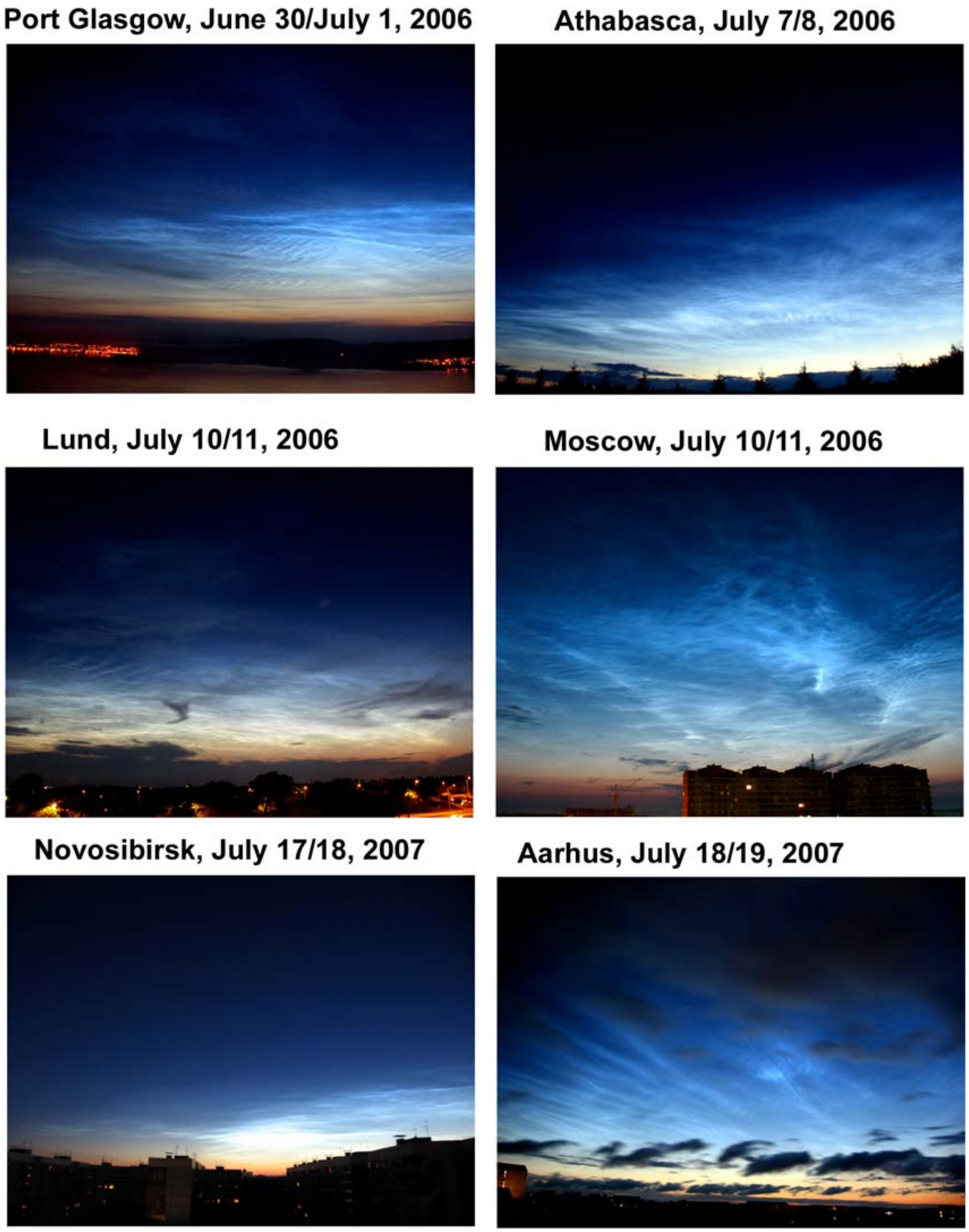
Figure 1. Map demonstrating locations of NLC cameras in 2006 and 2007: 1 – Novosibirsk, Russia (54°N52'; 83°E06'); 2 – Moscow, Russia (56°N00'; 37°E29'); 3 – Lund, Sweden (55°N43'; 13°E13'); 4 – Aarhus, Denmark (56°N10'; 10°E12'); 5 – Port Glasgow, Scotland (55°N56'; 04°W41'); 6 – Athabasca, Canada (54°N44'; 113°W19'). The thick curve represents schematically the 2-day planetary wave with zonal wavenumber 3 (see the text).

After the end of the NLC season all images are processed to obtain the statistics of NLC characteristics. At present the following parameters are estimated when NLCs occur: time of appearance and disappearance of NLCs, the NLC brightness by a 5-point scale to match the traditional visual brightness estimation, morphological forms and meteorological conditions during the night. As the NLC brightness in an image is visually estimated, this value has been carefully compared with visual brightness estimation made by independent observers around the world (www.nlcnet.co.uk), specifically for those nights when NLCs have been observed both by our cameras and observers located close to our cameras. The typical difference in the NLC brightness estimation is 1 point that is acceptable for purposes of the present study. We wish to emphasize that we process the NLC brightness in an image to match the traditional visual brightness values because at the present stage it is necessary to assess if it is possible to extend visually estimated long-term NLC data sets with values obtained with a modern photographic technique. As will be shown below the NLC brightnesses estimated with an image and eye are comparable. In the near future we plan to assess the NLC brightness in the absolute photometric value by using the brightness of the prominent circumpolar star Capella which is seen in the twilight sky in all images during the whole summer season.

We should emphasize that meteorological conditions are derived for each observed night independently of the presence or absence of NLCs. As will be shown (and it has been repeatedly shown (Romejko et al., 2003; Dalin et al., 2006a, 2006b)) the estimation of weather conditions is of importance for the NLC statistics.

3. Data analysis

Examples of bright NLC displays taken our cameras are shown in Panel 1. Bright NLCs represent a spectacular show inherent to observations of all our sites: clouds begin to appear before midnight (usually between 23 and 24 LT) and last during the entire night up to 04 LT in the morning, with clouds filling the whole area of the twilight sky; a lot of bands (atmospheric gravity waves) comprise a complex interference surface of waves of different scales from a few tens kilometers up to several hundred km (Witt, 1962; Hines, 1968; Grishin, 1967; Dalin et al., 2004), with waves propagating in different directions, Panel 1. Examples of bright NLC displays taken with NLC cameras in the northern hemisphere.



disappearing and appearing again, and sometimes changing their scale. Sometimes one can see short wavelength structures (a few km) which are thought to be Kelvin-Helmholtz waves caused by local wind shears (Hines and Reddy, 1967). Data from all our sites demonstrate that there are a lot of short-lived NLC occurrences of faint and moderate brightness. Life time of such clouds is from several tens minutes up to 1 hour. Such clouds are represented by several bands (gravity waves) that may appear at any area in the twilight sky and at any time of night, but they prefer to appear after midnight. As it is expected, due to the general wind circulation in the summer mesosphere, the general direction of NLC propagation is from northeast to southwest. However, there have been found that in 10-20% of all NLC cases at each observational site NLCs have been moving in approximately the opposite direction from west to east. It is not clear so far what atmospheric processes are responsible for such retrograde motion and this anomaly should be studied in the future. Note that the NLC camera in Athabasca often registers the aurora together with NLC due to its closer position to the aurora oval.

It is a common feature for each site that in most cases NLCs are observed within the limited elevation angle range between 3 and 30 degrees. This range corresponds to NLCs located above Earth in the latitude range between 58 and 63 degrees. Only in a few cases NLCs being extremely bright and extensive are observed more than 30° above the horizon and at the upper level of the field of view of cameras. The lower level is usually limited by a haze, trees, or buildings.

Our cameras have the limited angle of view in azimuth: 42° for Moscow, Aarhus, Port Glasgow and 78° for Novosibirsk and Athabasca. But this is certainly enough to register the majority of NLC occurrences due to the fact that NLCs are moving phenomena and there is a high probability to catch some part of NLC field with the cameras. The observers located close to our sites report NLC fields which are completely out of the field of view of cameras in 1-2 cases per season for each site.

The total statistics of NLC observations for each site are presented in Table 1. The total data series including NLC occurrences, their brightness and weather conditions for each site are resented below in Fig. 2 and 3 for 2006 and 2007, respectively.

Table 1. The total statistics of NLC observations for 2006 and 2007.

2006		2007	
Moscow	30	Moscow	29
Lund	30	Aarhus	14
Port Glasgow	36	Port Glasgow	29
Athabasca	28	Athabasca	24
		Novosibirsk	27

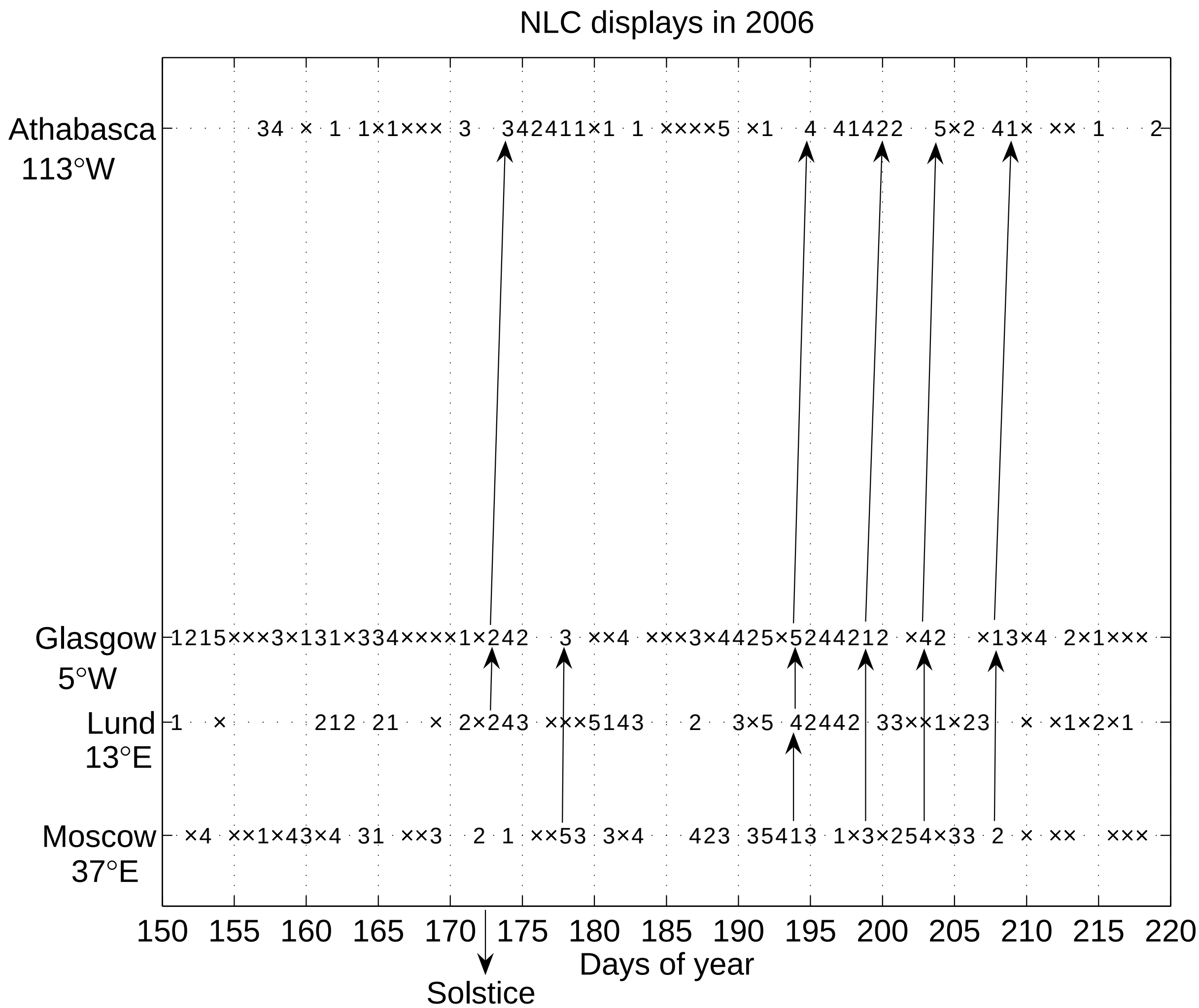


Figure 2. All NLC displays observed in Moscow, Lund, Port Glasgow and Athabasca in 2006. The numbers stand for the maximal brightness of NLCs (on a five point scale) on a given night. Crosses are nights with bad weather. Dots are an absence of NLCs on clear nights.

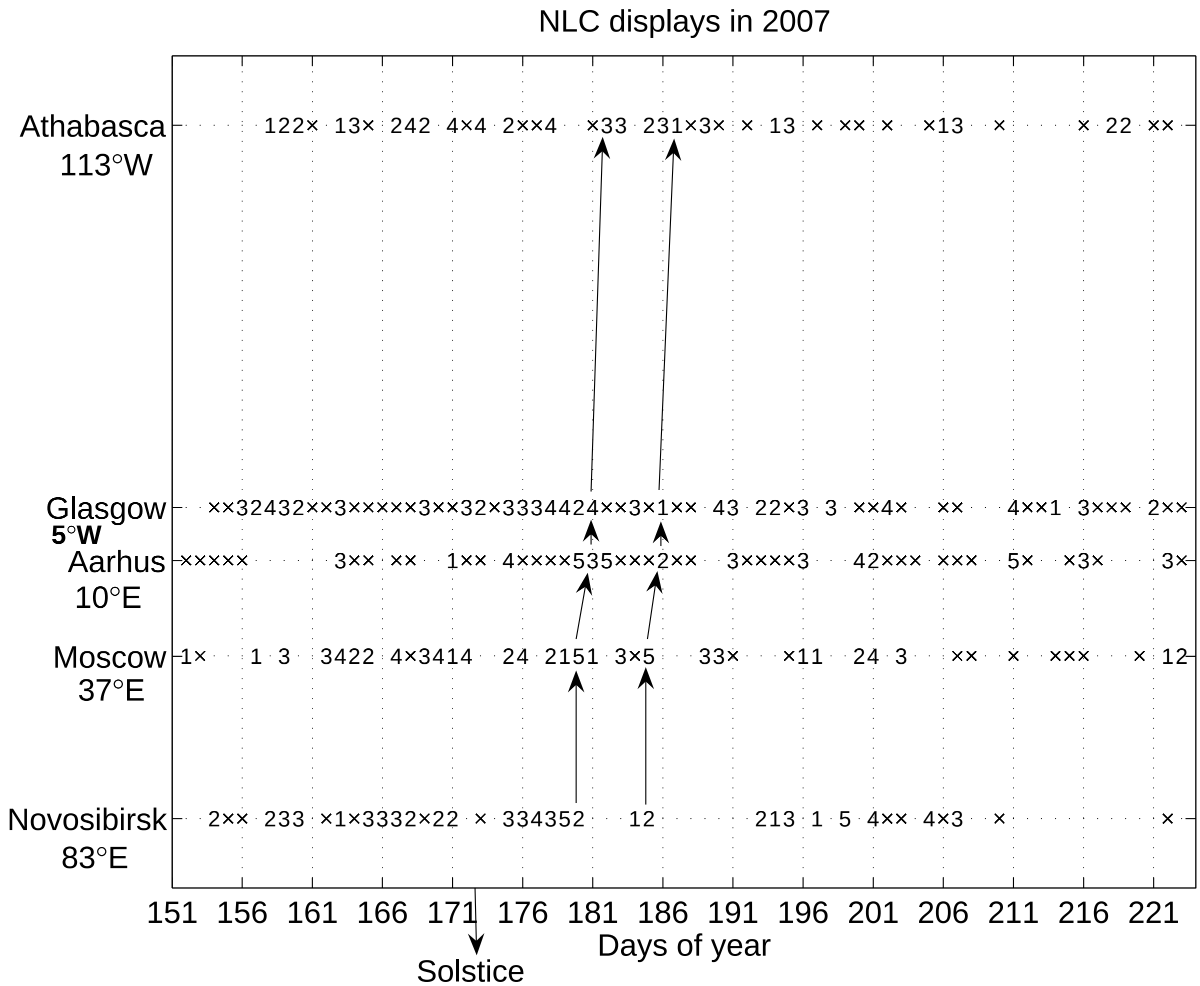


Figure 3. All NLC displays observed in Novosibirsk, Moscow, Aarhus, Port Glasgow and Athabasca in 2007. The numbers stand for the maximal brightness of NLCs (on a five point scale) on a given night. Crosses are nights with bad weather. Dots are an absence of NLCs on clear nights.

It is worthwhile to study if it is possible to extend visually estimated long-term NLC data sets with values obtained with a photographic technique. The yearly accumulated time series of the Moscow NLC occurrence rate is presented in the upper panel of Fig. 4. The detailed description of the Moscow NLC database is given by Romejko et al., 2003. Note that this database includes observations from 25 May to 25 July of each year and therefore Figure 4 does not include NLC displays made with the Moscow camera which out of this period (one NLC event in 2006 and 2007). One can see a clear increase of the

NLC number, 29 cases in 2006 and 28 cases in 2007, more than twice the totals of previous years. However, if one divides the NLC number by the number of clear and semi-clear weather nights for each year (that is the probability to see NLCs on a clear night), we obtain a completely different picture: the normalized NLC number of 2006 and 2007 is still less than the absolute maxima in the NLC probability of 1994 and 1997 (Fig. 4, the lower panel). It means that the apparent absolute maximum in the NLC number of 2006 is mainly explained by a large number of clear weather nights; the weather factor disturbs the real signal in NLC data and the weather influence has to be removed from the NLC statistics.

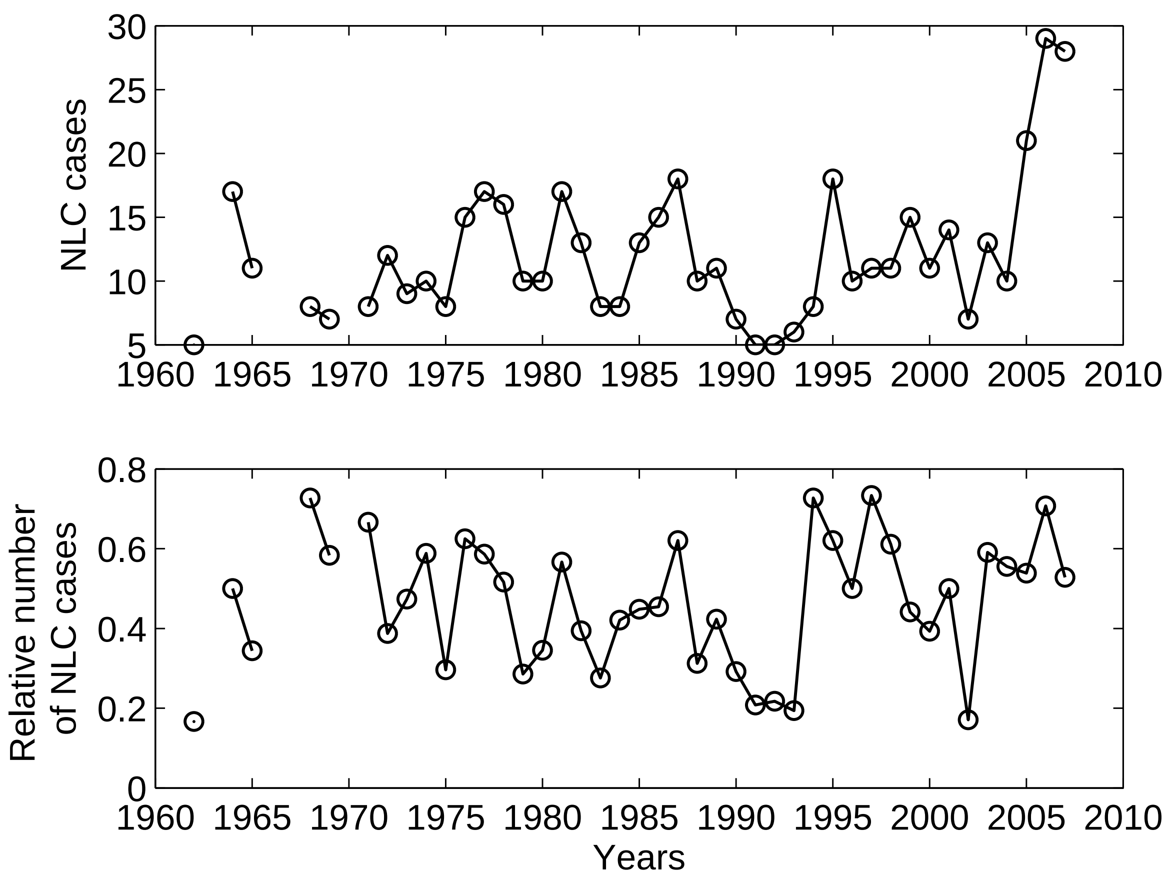


Figure 4. The upper panel: yearly variation in the total number of nights with NLC in Moscow. The lower panel: time series of normalized NLC frequency (normalized by the number of clear weather nights) in Moscow.

Now it is of interest to take a look at the sets of the NLC yearly accumulated brightness shown on the upper panel of Fig. 5. Again we see more than a doubling in the NLC brightness of 2006. The normalized NLC brightness (by the number of clear and semi-clear nights) also has its absolute maximum in 2006 since the beginning of Moscow observations in 1962 (lower panel of Fig. 5). It means that brightness of NLCs is really enhanced in 2006. Indeed, many observers worldwide noted extremely bright clouds at both the beginning and the end of the NLC season.

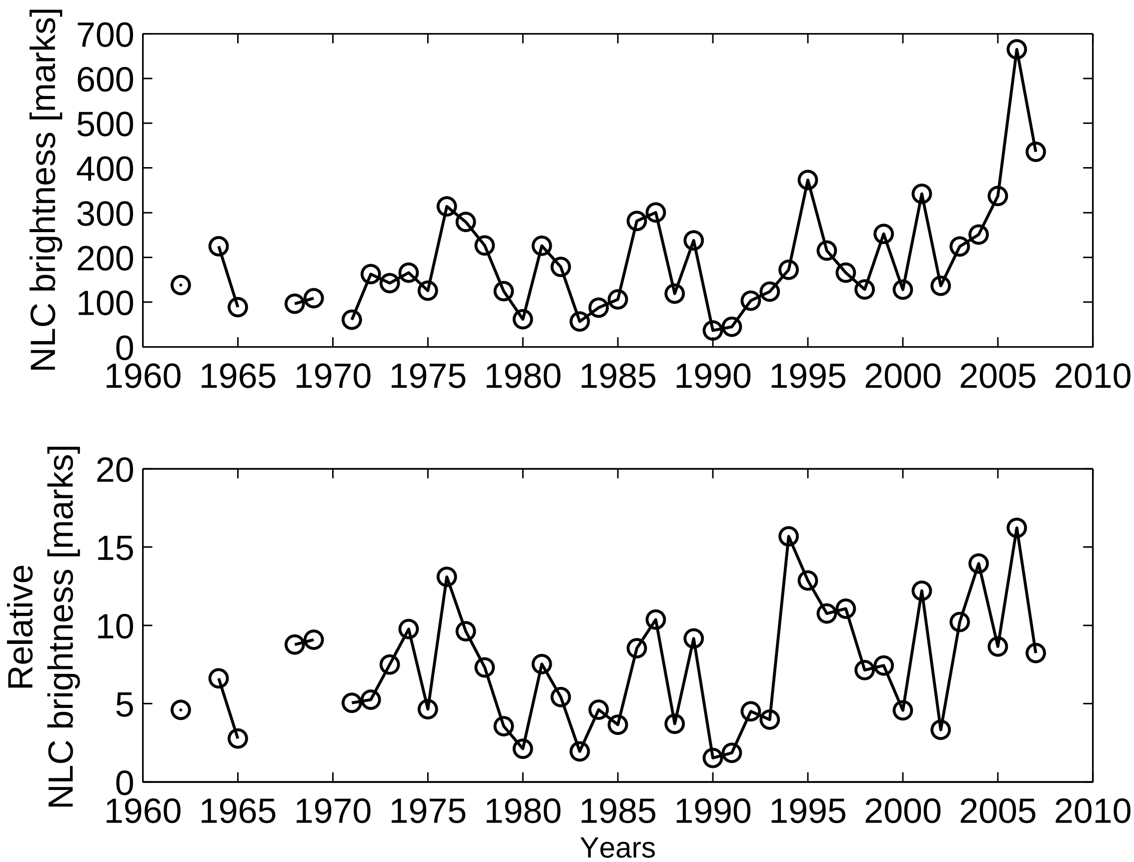


Figure 5. The upper panel: yearly variation of the NLC brightness in Moscow. The lower panel: time series of normalized NLC brightness (normalized by the number of clear weather nights) in Moscow.

The influence of gravity and planetary wave activity on the NLC occurrence around the globe can be investigated using the data from widely-separated cameras located along the same latitude circle. To make a correct analysis, it is necessary to separate bright or extensive NLCs from faint ones for the following reason. Faint NLCs are usually represented by single bands that are limited in extent. These bands are caused by small-scale gravity waves with horizontal and vertical wavelengths of several tens and a few km respectively (Witt, 1962; Grishin, 1967; Dalin et al., 2004). The planetary waves have horizontal wavelengths of several thousand kilometers and vertical scales typically of several tens (Salby, 1984). Thus, in the present study we consider carefully faint NLC displays, representing gravity waves, and bright/extensive NLC cases caused by large-scale wave processes.

Figure 6 demonstrates histograms of time intervals between two successive NLC displays observed in Moscow, Lund, Port Glasgow and Athabasca in 2006. All observed NLCs (faint, moderate and bright) are collected for making this plot. On the left-hand panels one can see that 1-day and 2-day time intervals dominate between NLC displays at all sites. Also, one can see more or less significant amount of 3-day, 4-day, 5 day and 6-days time intervals varying from site to site. However, the representation given is contaminated by weather tropospheric conditions. Indeed, for example, a 2-day time interval may be either a real 2-day interval with an absence NLCs on a clear night between two successive NLC cases or a sum of two 1-day intervals separated by a night with bad weather. That is why it is necessary to eliminate weather condition for estimating the significance of time intervals between NLC displays.

This can be done in the following way. The effective number (P) of a time interval may be represented by the following relation:

$$P = \frac{N_{clear}}{(I-1)} \tag{1}$$

where N_{clear} is the total number of clear or semi-clear nights inside all I-day intervals, I is the value of a specified time interval. In other words, the P-number is the number of time intervals free of bad weather conditions. For example, if we have three 3-day time intervals and the sum of clear nights inside these intervals is 4, then we get a ratio: 4/(3-1)=2, i.e. there are only two 3-day time intervals which are not contaminated by the tropospheric cloudiness, and if the sum of clear nights is equal to 1, then we get a ratio: 1/(3-1)=0.5, i.e. there are no 3-day time interval free of a weather factor. A 1-day time interval is always significant with a 100% significance and that is why it is not explained by the given relation.

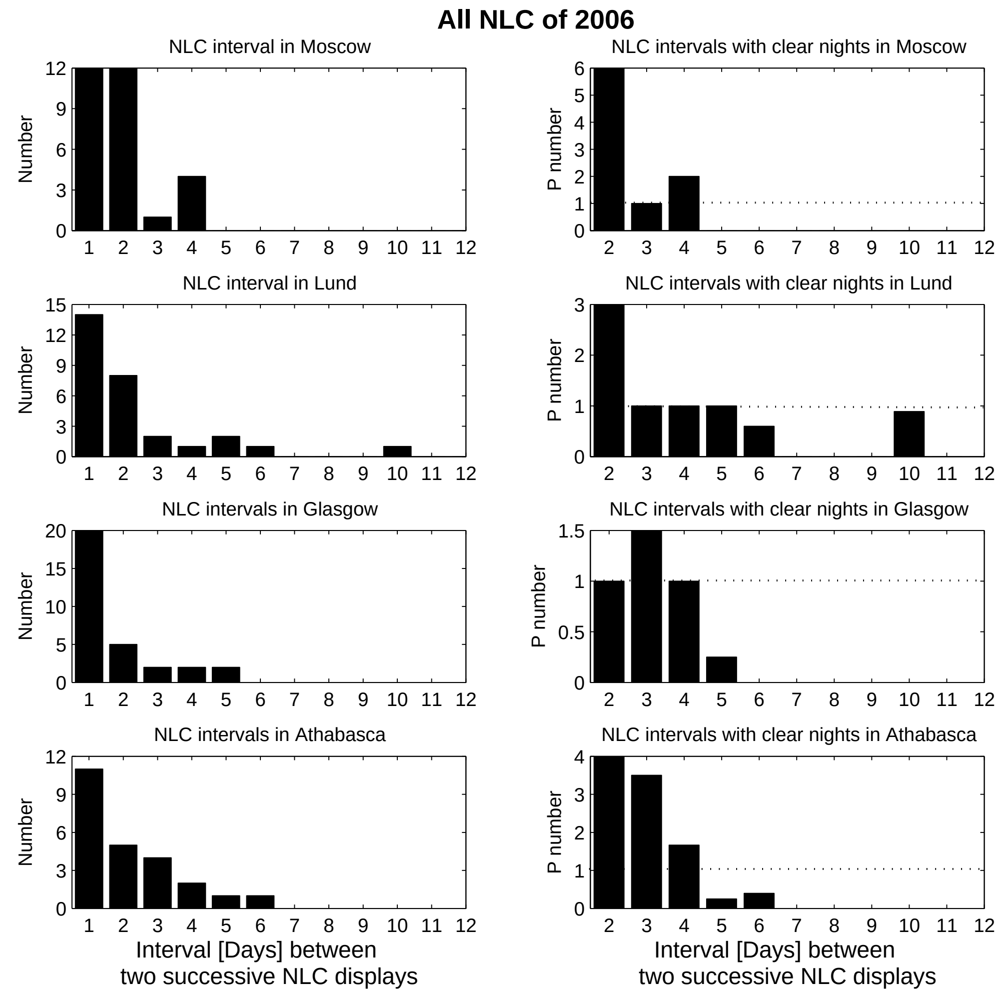


Figure 6. Histograms of time intervals between two successive NLC displays observed from Moscow, Lund, Port Glasgow and Athabasca in 2006.

The effective number of time intervals is presented on the right-hand panels of Fig.6. A horizontal dotted line, equal to 1, defines a single time interval which is free of weather conditions. Below this line any time interval is not significant. One can see that the largest number of intervals is for a 2-day time interval for all sites except for Port Glasgow for which a 3-day interval significantly dominates. Remember that all 1-day time intervals illustrated on the left-hand panels are 100% significant. The Moscow data demonstrate two 4-day intervals and the Athabasca data show three 3-day and two 4-day intervals free of a weather factor.

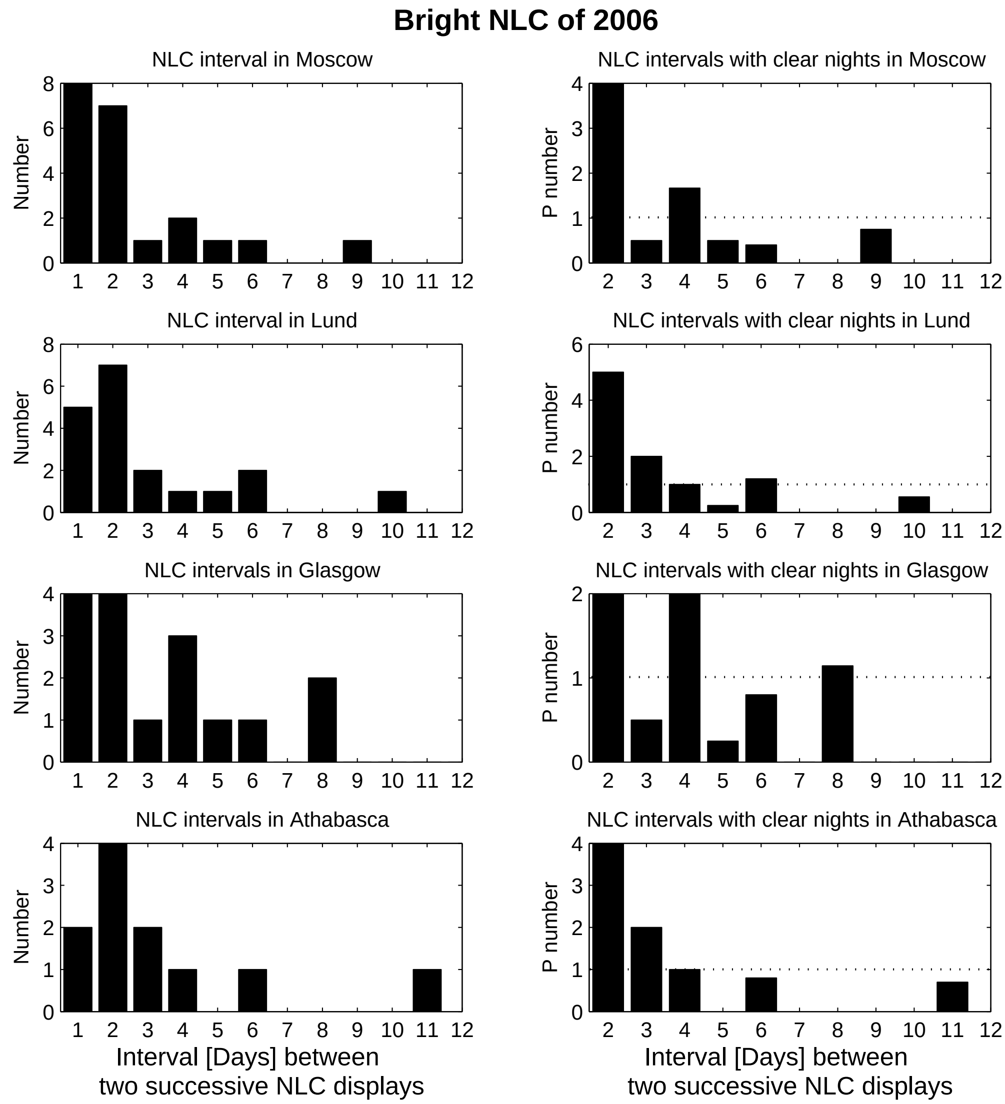


Figure 7. Histograms of time intervals between two successive bright and/or extended NLC displays observed from Moscow, Lund, Port Glasgow and Athabasca in 2006.

Another picture is obtained if one regards bright NLCs only (Fig. 7). The left-hand panels show us that together with a 1-day time interval there is a large number of 2-day intervals. For the Lund and Athabasca data the number of 2-day time intervals is even dominating. The right-hand panels demonstrate that for all the data the largest number of significant intervals (not depending on tropospheric cloudiness) is for a 2-day time interval. Also, 3-day and 4-day intervals are seen to be significant from site to site. Note that for bright NLCs the number of 1-day intervals is rather suppressed comparing to NLCs of all brightnesses, but the number of 2-day intervals is at the same level and even more for some sites (Lund and Port Glasgow).

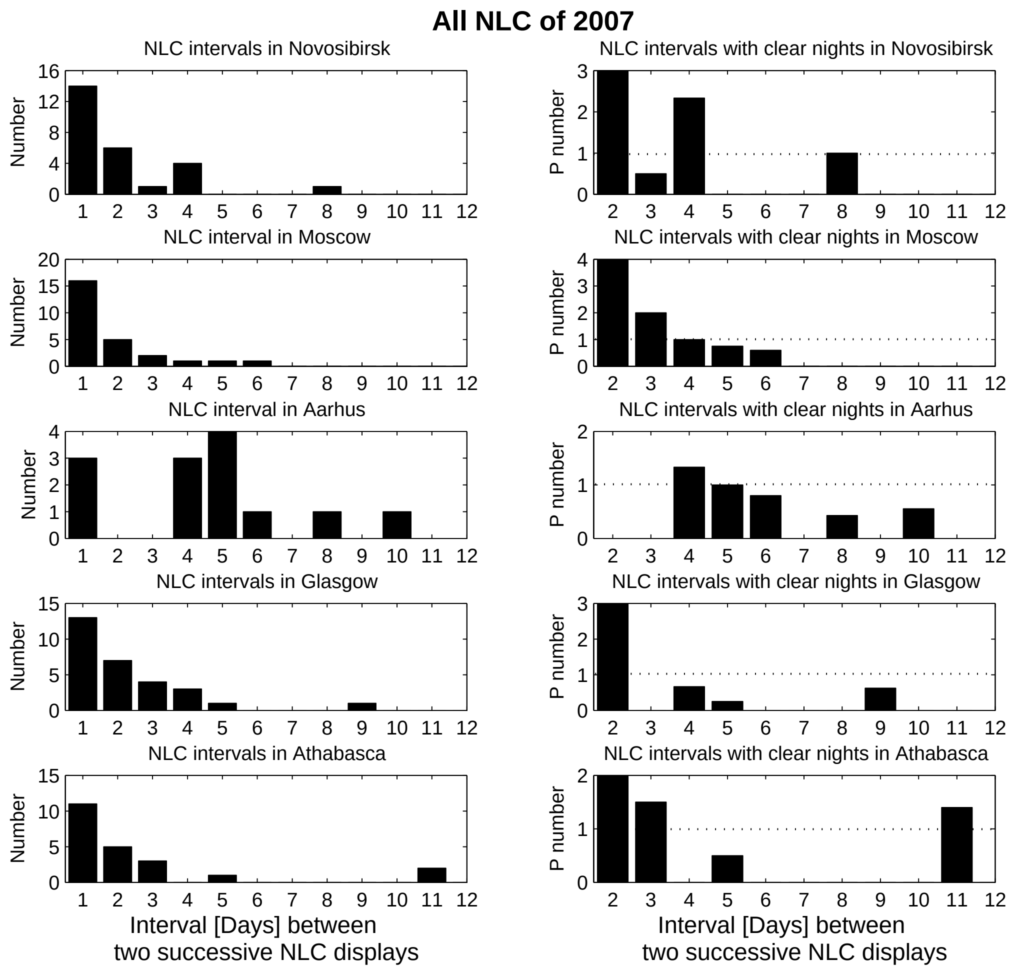


Figure 8. Histograms of time intervals between two successive NLC displays observed from Novosibirsk, Moscow, Aarhus, Port Glasgow and Athabasca in 2007.

Approximately the same picture is observed for 2007. For all NLC brightnesses (Fig. 8) the prevailing interval is a 1-day time interval. The right-hand panels demonstrate that a 2-day interval is significant for all sites except for Aarhus which is due to bad weather conditions at this site during summer of 2007. A 3-day interval is seen to be significant for observation made from Moscow and Athabasca as well as there is a 4-day interval for the Novosibirsk and Aarhus data. Bright NLCs (Fig. 9) tend to occur in 1-day and 2-day period; for some places 3-day, 4-day and 5-day periods are significant as well.

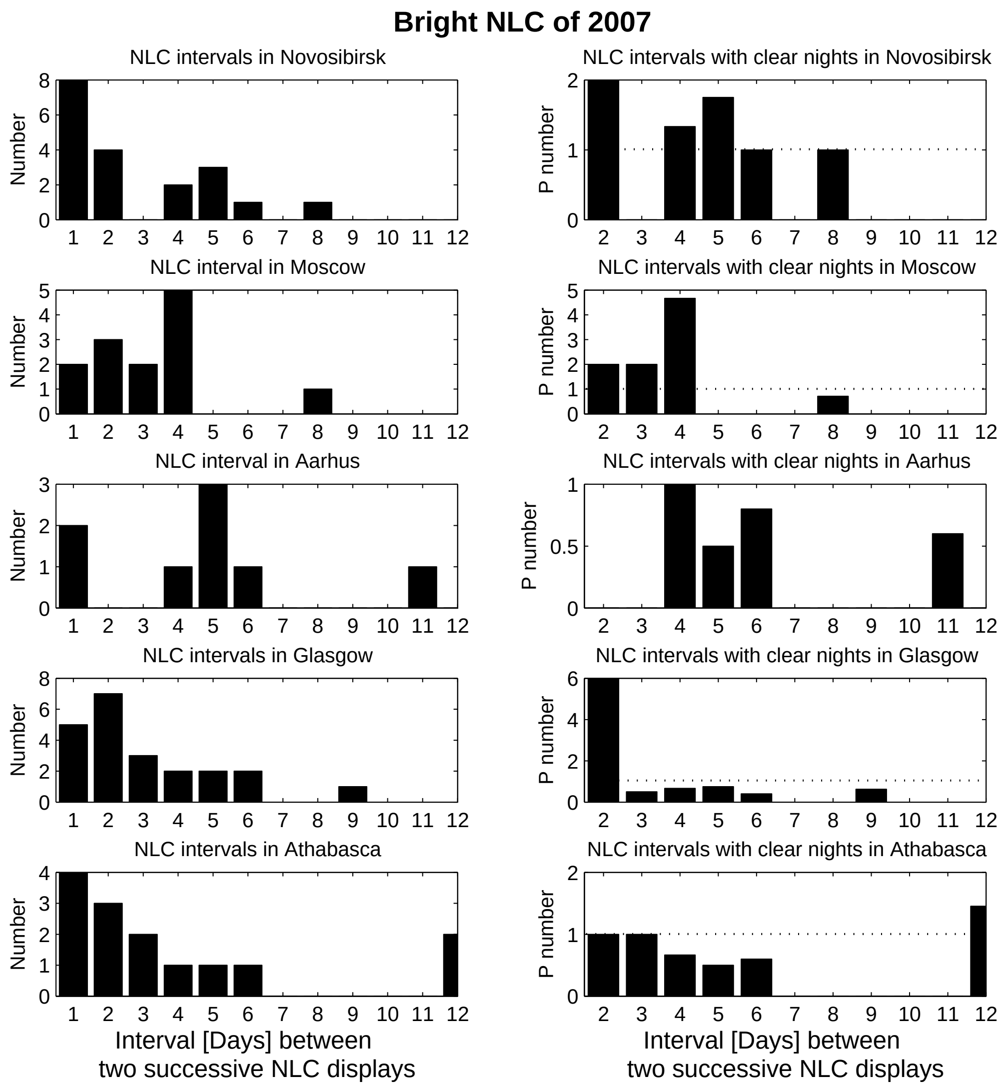


Figure 9. Histograms of time intervals between two successive bright and/or extended NLC displays observed from Novosibirsk, Moscow, Aarhus, Port Glasgow and Athabasca in 2007.

Summarizing the results of Fig. 6, 7, 8 and 9 one can conclude the following. Faint and moderate NLCs tend to occur on consecutive and also every 2 nights at each site, with the former dominating. Bright NLCs are seen to be observed mostly on consecutive and every 2 nights as well, but the latter is comparable with the former and, sometimes, even dominating. 3-day, 4-day, 5-day and 6-day time intervals seem to occur sporadically, from site to site and from year to year (at least when considering from 2006 and 2007), and are not prevailing periodicities between NLC displays. Exceptions are the Aarhus data of 2007 for which, due to bad weather conditions, 4-day and 5-day periodicities dominate, and the Moscow data of 2007 for bright NLCs for which the 4-day time interval prevails.

Looking at Fig. 2 and 3 one can note an interesting feature. NLCs tend to occur on the same night at all sites. Indeed, in 2006 from 28 NLC cases observed in Athabasca NLCs were seen in 21 cases at least from two other sites and even from three other sites (Moscow, Lund and Port Glasgow) when weather was clear on the same night. For 2007 we have the following statistics: from 24 NLC cases observed in Athabasca NLCs were seen in 12 cases at least from two other sites and sometimes from four sites (Novosibirsk, Moscow, Aarhus and Port Glasgow) on the same night. Note that weather conditions contaminate this statistics and if there were more clear nights at all sites there would be more "simultaneous" NLC observations along the latitude circle. From this statistics it follows that NLC tend to occur on one half of the latitude circle on the same night. This could be explained by either some global process or by a sporadic (independent from site to site) NLC activity.

We can apply a statistical approach to investigate whether NLC time series observed at different sites are dependent events or not. By definition (Bendat and Piersol, 1966) the random variables $x_1, x_2,\ldots, x_n$ are statistically independent if the joint probability function is a product of probability functions of variables:

$$P(x_1, x_2,\ldots, x_n)=P(x_1)P(x_2)\ldots P(x_n) \qquad (2)$$

NLCs were observed in Athabasca, Port Glasgow, Lund and Moscow in 2006. The NLC occurrences from Port Glasgow and Lund may be combined due to relatively close positions of these sites; this proximity eliminates weather factor in great extent. From Fig. 2 one can calculate that the probabilities to observe NLCs on a clear night are 0.52, 0.70, and 0.60 for Athabasca, Port Glasgow and Lund, and Moscow, respectively. Their product is equal to 0.22. The joint probability to see NLCs simultaneously from three sites is 0.38. The latter value is significantly larger than the former one meaning that the relation 2 is not valid. Thus, NLC displays observed from three sites in 2006 are not statistically independent.

In 2007 NLCs were observed in Athabasca, Port Glasgow, Aarhus, Moscow and Novosibirsk. We combine NLC occurrences from Port Glasgow and Aarhus due to close positions of these sites. From Fig. 3 one calculates that the probabilities to observe NLCs on a clear night are 0.44, 0.61, 0.48 and 0.44 for Athabasca, Port Glasgow and Aarhus, Moscow, and Novosibirsk, respectively. Their product is equal to 0.06. The joint probability to see NLCs simultaneously from four sites is 0.19. Again, the latter value is significantly larger than the former one, that is, the relation 2 is not valid. Thus, NLC displays observed from four sites in 2007 are not statistically independent as well.

4. Discussion

We have retrieved a significant number of 2-day time intervals at all sites. The 2-day interval might be associated with a well-known westward propagating quasi 2-day planetary wave of zonal wavenumber 3 (Muller and Nelson, 1978; Salby, 1981), but it is also possible this wave, sometimes, has a zonal wavenumber of 4 (Meek et al., 1996). Quasi 2-day variations are observed to be strongest in zonal and meridional wind components in the summer mesopause region (Jacobi et al., 1998).

Also, as we have shown, NLCs tend to occur over half of the latitude circle on the same night. This could be explained by some global and dynamic process leading to NLC occurrences and modulation of the NLC brightness on continental scales with an appropriate time shift. One of well-known global processes is the 2-day planetary wave. The 2-day wave with zonal wavenumber 3 or 4 travels westward 60° or 45° of longitude per day, respectively. This wave with three or four amplitude maxima around the globe can produce significant temperature (up to 8 K, Pogoreltsev, 1999) and wind (10-20 m/s, Jacobi et al., 1998; Pogoreltsev, 1999) variations around the mesopause at many sites around the globe including opposite sites (Novosibirsk and Athabasca) on the same night (remember, there is a time difference of 13 hours between Novosibirsk and Athabasca). Indeed, suppose one temperature maximum of the 2-day wave with zonal wavenumber equal to 4 is located over Novosibirsk. The 2-day wave travels ~24° in longitude for 13 hours that means the third maximum (separated from the first one by 180°) of the wave has the following location: 180°+24°=204°, that is very close to the difference of longitudes of 196° between Novosibirsk and Athabasca. The estimations of location of the 2-day wave phase relative to Novosibirsk as seen at local midnight above each site are given in Table 2. One can see from Table 2 that the 2-day planetary wave with zonal wavenumber 3 cannot explain the NLC occurrence at opposite sites of a latitude circle. Indeed, if one wave maximum is located above Novosibirsk then wave minima cover all other sites (Moscow, Lund, Aarhus, Port Glasgow and Athabasca). However, NLC occurrences seen in Moscow, Lund, Aarhus, Port Glasgow and Athabasca on the same night (see the thick curve in Fig. 1), and in Novosibirsk on the next night might be explained with such a wave because all these sites belong to wave minima. Therefore, retrieving the 2-day wave from our data depends critically on both the positions of available sites and on the initial phase of the 2-day wave relative to these sites. That is why one can expect that sometimes the crests or troughs of westward propagating 2-day planetary wave with zonal wavenumber 3 might perfectly match the locations of all our sites leading to NLC displays on the same and next night; sometimes the wave crests or troughs will match not all or even none of the sites, resulting in NLC occurrences over fewer of our sites. This outcome is actually what we observe in our data.

Table 2. The 2-day planetary wave with zonal wavenumber (m) 3 and 4. The wave phase is relative to Novosibirsk as observed at local midnight above each site.

	Novosibirsk λ=83°	Moscow λ=37°	Lund/Aarhus λ=13°/10°	Port Glasgow λ= -5°	Athabasca λ= -113°	Novosibirsk λ=83°
m=3	0°	115.5°	172.5°/181.5°	219°	360° + 130.5°	180°
m=4	0°	161.5°	242.5°/254.5°	307°	360° + 326.5°	180°

The 2-day wave with zonal wavenumber 4 can account for the NLC occurrence on the same night in Novosibirsk, Port Glasgow and Athabasca due to wave maxima cover these sites (see Table 2). It is a little bit difficult to explain the NLC occurrence in Lund and Aarhus since these sites are located in a wave minimum (but rather close to the neutral line of a wave) and it is difficult to explain the NLC occurrence in Moscow because a wave minimum covers Moscow. But we should note that we have regarded a right geometrical pattern of a wave; in reality the horizontal pattern of the 2-day planetary wave represents a complex shape with long "tongues" (Rodgers and Prata, 1981). Thus, the 2-day planetary wave with zonal wavenumber 4 can explain NLC occurrences and modulation of the NLC brightness on opposite sites of a latitude circle as well as at other intermediate sites on the same night.

Our data demonstrate that 4-day, 5-day and 6-day time intervals are present in the NLC periodicity. A 5-day period is well-known in NLCs (Gadsden, 1985; Sugiyama et al., 1996; Kirkwood and Stebel, 2003; Merkel et al., 2003) and is usually associated with a free traveling quasi 5-day planetary wave of zonal wave number 1. Note that theoretical considerations (e.g. Salby, 1981) demonstrate that the periods of 5-day planetary waves lie in the interval of 4.4-5.7 days (due to local nonuniformities and a Doppler-shift effect). This is confirmed by observational data, namely, by a 4-6-day period wind fluctuation in the upper mesosphere and mesopause (Hirota et al., 1983; Jacobi et al., 1998). Thus, we cannot expect a precise 5-day period in the NLC occurrence frequency but rather a spread between 4 and 6 days. Although a 5-day period was noted in NLCs, it was done based on the statistics which did not include information on weather conditions, and therefore a 5-day period may be readily represented by combinations of 1- and 2-day time intervals that are found to be significant and prevailing in NLC occurrences in 2006 and 2007.

Merkel et al. (2003) have demonstrated a strong influence of the 5-day planetary wave on PMCs. At the same time, in this paper there was found the temporal and latitudinal structure of the 5-day wave in the mesopause which was variable from year to year during 1998-2001. Also, strong seasonal and yearly variations of the amplitude of the 5-day wave were found in the upper stratosphere during 1992-2001 (Fedulina et al., 2004). Von Savigny et al. (2007) have reported on simultaneous measurements of the quasi 5-day wave in NLCs and the mesopause temperature in the northern hemisphere during summer of 2005. They have used Envisat satellite limb scattering measurements to detect NLCs and the Aura satellite data to measure the mesopause temperature. They have found that for some periods (before and around the solstice) the quasi 5-day wave signatures in NLCs were likely caused by quasi 5-day wave signatures in the temperature field that is these wave processes anti-correlated. However the 5-day wave patterns were irregular after the solstice. Sometimes they observed a phase shift and even the clear correlation between quasi 5-day oscillations in NLCs and temperature. Von Savigny et al. (2007) have noted high variability of NLCs (2-3 days) for certain parts of the 2005 NLC season and questioned whether this variability may be related to the 2-day planetary wave. Merkel et al. (2008) have found evidence of the presence of the 2-day and 5-day planetary waves in both PMCs and mesospheric temperature. These authors have used the SNOE satellite and TIMED (SABER instrument) spacecraft data to observe PMCs at high latitudes 68-80° and retrieve temperature, respectively. Merkel et al. (2008) have found that during the 2002 and 2003 summer mesosphere seasons the temperature perturbations due to 2-day and 5-day waves were small (2.0-3.5 K) but had a significant effect on the PMC brightness variation.

Numerical simulations (Grollmann, 1992) have shown that the propagation of the 5-day wave is sensitive to the mean background wind, although this wave has a large phase velocity and therefore should not filtered by the westward mean wind flow in the summer mesosphere.

Thus, it is possible that during June and July of 2006 and 2007 the activity of the 5-day planetary wave was quite low in the mesopause at latitudes 58-63°. It is possible to trace some particular 4-5-day periods in the rotation of NLC patterns (selected by heavy lines in Fig. 2 and 3) but these periods are not unambiguously determined. We have to accumulate more statistics to extract significant 5-day periodicity in the NLC occurrence to connect it with the 5-day planetary wave. The most important consideration is that the absolute number of the 2-day time interval and its significance is more than the absolute number of 4-6-day intervals and their significances in 2006 and 2007. Exceptions are the Aarhus data of 2007 for which, due to bad weather conditions, 4-day and 5-day periodicities dominate, and the Moscow data of 2007 for bright NLCs for which the 4-day time interval prevails. The larger number of the 2-day intervals points to the dominating activity of the 2-day planetary wave in the summer mesopause in 2006 and 2007.

We have found that NLC occurrences observed around the globe are not statistically independent but there is a global process responsible for the simultaneous NLC occurrences at continental scales, and as we have shown, the most probable candidate is the 2-day planetary wave.

Our data demonstrate that bright NLCs usually appear before midnight and stay visible up to 04:00 LT. The origin of night-by-night NLC repetitions (during short burst periods of 3-5 nights) is not clear so far.

A dominating 1-day time interval (and less) implies that a scheme of the oscillatory formation of NLCs (if it is valid) takes much less time than it was estimated in one-dimensional modeling by Sugiyama et al. (1996) who have found a 5.6-day periodicity. This situation suggests that one-dimensional microphysical models of NLCs should not be regarded as a realistic one, describing observational properties of NLC in a good way, but a three-dimensional modeling should be considered (for example, Berger and von Zahn, 2002). Indeed, the horizontal transport of ice particles, water vapor and condensation nuclei is much larger than vertical winds and vertical turbulent diffusion, and may be as important as wave-induced temperature variations. In particular, Kirkwood and Stebel (2003) have found that NLCs are most often observed when the wave-induced winds blow strongly from the north. However, none of the three-dimensional published simulations on the NLC formation and development take into account wind and temperature perturbations due to planetary waves. The temperature variations due to 2-day, 5-day, and 16-day planetary waves (5-15 K) are much larger than those of solar thermal tides (1-2 K), which are regarded in theoretical studies of NLCs. Also, lunar oscillations are found to be important for the NLC occurrence frequency (Kropotkina and Shefov, 1976; Gadsden and Schröder, 1989; Dalin et al., 2006b), which have not been included into theoretical considerations so far. Thus, the environment, in which NLC particles are formed and transported, is far from a realistic representation at present time, and significant efforts for improving of the existing three-dimensional models have to be done in the future.

4. Summary

For the first time we present an analysis of observations of NLCs obtained with an inter-continental network of automatic digital cameras. The advantage of this technique is that these cameras are located along the same latitude circle (55-56°) producing comparable measurements of high quality. We have analyzed the data for the summers of 2006 and 2007 and summarize the following.

1. The propagation of the 2-day planetary wave with zonal wavenumber 3 and 4 can partly explain the NLC occurrence frequency, NLC geographical distribution and NLC brightness variation. The effect of well-know 5-day planetary wave on NLCs seems to be much less than that of the 2-day wave, at least during summers of 2006 and 2007. We have to accumulate more statistics to extract significant 5-day periodicity in the NLC occurrence to connect it with the 5-day planetary wave.
2. There is a global process responsible for the simultaneous (on the same night) NLC occurrences at continental scales along the latitude band of 58-63° and the most probable candidate is the 2-day planetary wave.
3. Our data demonstrate that bright NLCs usually appear before midnight and stay visible up to 04:00 LT. The origin of night-by-night NLC repetitions (during short burst periods of 3-5 nights) is not clear so far.

Acknowledgements

We wish to thank the reviewers for constructive comments on the original manuscript. We are grateful to Sheila Kirkwood for equipment support and useful comments and discussions during the manuscript preparation. We gratefully acknowledge Ivan Scheblykin for his support of the NLC observations with a digital camera in the south of Sweden, Lund University. Thanks are due to Andrei Reshetnikov, Alexander Dalin, Olga Dalina, Andrei Retivov, Ilya Chelnokov and Ivan Voronov for supporting the NLC observations with a digital camera in Moscow Region. We are also grateful to Takuya Sugiyama for his equipment support of one supplementary NLC camera located near Moscow (Zvenigorod).

References

Bendat, J.S., and Piersol, A.G., 1966. Measurements and analysis of random data. John Wiley & Sons, New York.

Berger, U., and von Zahn, U., 2002. Icy particles in the summer mesopause region: three-dimensional modeling of their environment and two-dimensional modeling of their transport. Journal of Geophysical Research 107 (A11), 1366, doi:10.1029/2001JA000316.

Berger, U., and Lübken, F.-J., 2006. Weather in mesospheric ice layers. Geophysical Research Letters 33, L04806, doi:10.1029/2005GL024841.

Carbary, J. F., Morrison, D., Romick, G. J., 2003. Maps of polar mesospheric clouds. Journal of Geophysical Research 108 (D8), 8446, doi:10.1029/2002JD002255.

Dalin, P., Kirkwood, S., Moström, A., Stebel, K., Hoffmann, P., Singer, W., 2004. A case study of gravity waves in noctilucent clouds. Annales Geophysicae 22, 1875-1884.

Dalin, P., Kirkwood, S., Andersen, H., Hansen, O., Pertsev, N., Romejko, V., 2006a. Comparison of long-term Moscow and Danish NLC observations: statistical results. Annales Geophysicae 24, 2841-2849.

Dalin, P. A., Pertsev, N. N., Romejko, V. A., 2006b. Significance of lunar impact on noctilucent clouds. Journal of Atmospheric and Solar-Terrestrial Physics 68, 1653-1663, doi:10.1016/j.jastp.2006.06.005.

DeLand, M. T., Shettle, E. P., Thomas, G. E., Olivero, J. J., 2003. Solar backscattered ultraviolet (SBUV) observations of polar mesospheric clouds (PMCs) over two solar cycles. Journal of Geophysical Research 108(D8), 8445, doi:10.1029/2002JD002398.

Espy, P. J., and Witt, G., 1996. Observation of a quasi 16-day oscillation in the polar summer mesospheric temperature. Geophysical Research Letters 23, 10, 1071-1074.

Fedulina, I. N., Pogoreltsev, A. I., Vaughan, G., 2004. Seasonal, interannual and short-term variability of planetary waves in Met Office stratospheric assimilated fields. Quarterly Journal of the Royal Meteorological Society 130, 2445-2458.

Gadsden, M., 1985. Observations of noctilucent clouds from North-West Europe, Annales Geophysicae 3, 1, 119-126.

Gadsden, M., and Schröder, W., 1989. Noctilucent Clouds. Springer-Verlag, New York, 165 pp.

Grishin, N. I., 1967. Noctilucent clouds. Proceedings of International Symposium, edited by I. A. Khvostikov and G. Witt, VINITI, Moscow, 193-198.

Grollmann, Th., 1992. Wechselwirkung freier moden, gezeiten und schwerewellen in der mittleren atmosphäre. Mitteilungen des Instituts für Geophysik und Meteorologie der Universität Köln 84, 141 p.

Hines, C. O., and C. A. Reddy, 1967. On the propagation of atmospheric gravity waves through regions of wind shear, Journal of Geophysical Research 72, 3, 1015-1034.

Hines, C. O., 1968. A possible source of waves in the noctilucent clouds, Journal of the Atmospheric Sciences 25, 937-942.

Hirota, I., Maekawa, Y., Fukao, S., Fukuyama, K., Sulzer, M. P., Fellous, J. L., Tsuda, T., Kato, S., 1983. Fifteen-day observation of mesospheric and lower thermospheric motions with the aid of the Arecibo UHF radar. Journal of Geophysical Research 88, 6835-6842.

Jacobi, Ch., Schminder, R., Kürschner, D., 1998. Planetary wave activity obtained from long-period (2-18 days) variations of mesopause region winds over Central Europe (52°N, 15°E). Journal of Atmospheric and Solar-Terrestrial Physics 60, 1, 81-93.

Kirkwood, S., and Stebel, K., 2003. Influence of planetary waves on noctilucent clouds occurrence over NW Europe. Journal of Geophysical Research 108, 8440, doi:10.1029/2002JD002356.

Kropotkina, Ye. P., and Shefov, N. N., 1976. Influence of lunar tides on the probability of appearance of noctilucent clouds. Russian Academy of Sciences, Izvestiya Atmospheric and Oceanic Physics 11, 741-742.

Meek, C.E., Manson, A.H., Franke, S.J., Singer, W., Hoffmann, P., Clark, R.R., Tsuda, T., Nakaura, T., Tsutsumi, M., Hagan, M., Fritts, D.C., Isler, J. and Portnyagin, Yu.I., 1996. Global study of northern hemisphere quasi-2-day events in recent summers near 90 km altitude. Journal of Atmospheric and Terrestrial Physics 58, 1401-1411.

Merkel, A.W., Thomas, G. E., Palo, S. E., Bailey, S. M., 2003. Observations of the 5-day planetary wave in PMC measurements from the Student Nitric Oxide Explorer Satellite. Geophysical Research Letters 30, 4, 1196, doi:10.1029/2002GL016524.

Merkel, A., Garcia, R. R., Bailey, S., and Russell III, J. M., 2008. Observational studies of planetary waves in PMCs and mesospheric temperature measured by SNOE and SABER, Journal of Geophysical Research, doi:10.1029/2007JD009396, in press.

Muller, H.G., and Nelson, L., 1978. A travelling quasi 2-day wave in the meteor region. Journal of Atmospheric and Terrestrial Physics 40, 761-766.

Pogoreltsev, A., 1999. Simulation of planetary waves and their influence on the zonally averaged circulation in the middle atmosphere. Earth Planets and Space 51, 773-784.

Rodgers, C.D., and Prata, A., 1981. Evidence for a traveling 2-day wave in the middle atmosphere. Journal of Geophysical Research 86, 9661-9664.

Romejko, V.A., Dalin, P.A., Pertsev, N. N., 2003. Forty years of noctilucent cloud observations near Moscow: database and simple statistics. Journal of Geophysical Research 108 (D8), 8443, doi:10.1029/2002JD002364.

Salby, M. L., 1981. Rossby normal modes in nonuniform background configurations. Part II: equinox and solstice conditions. Journal of the Atmospheric Sciences 38, 1827-1840.

Salby, M. L., 1984. Survey of planetary-scale traveling waves: the state of theory and observations, Reviews of Geophysics and Space Physics 22, 2, 209-236.

Sugiyama, T., Murako, Y., Sogawa, H., and Fukao, S., 1996. Oscillations in polar mesospheric summer echoes and bifurcation of noctilucent cloud formation. Geophysical Research Letters 23, 653-656.

von Savigny, C., Robert, C., Bovensmann, H., Burrows, J.P., and Schwartz, M., 2007. Satellite observations of the quasi 5-day wave in noctilucent clouds and mesopause temperatures. Geophysical Research Letters 34, L24808, doi:10.1029/2007GL030987.

Witt, G., 1962. Height, structure and displacements of noctilucent clouds. Tellus XIV, 1, 1-18.