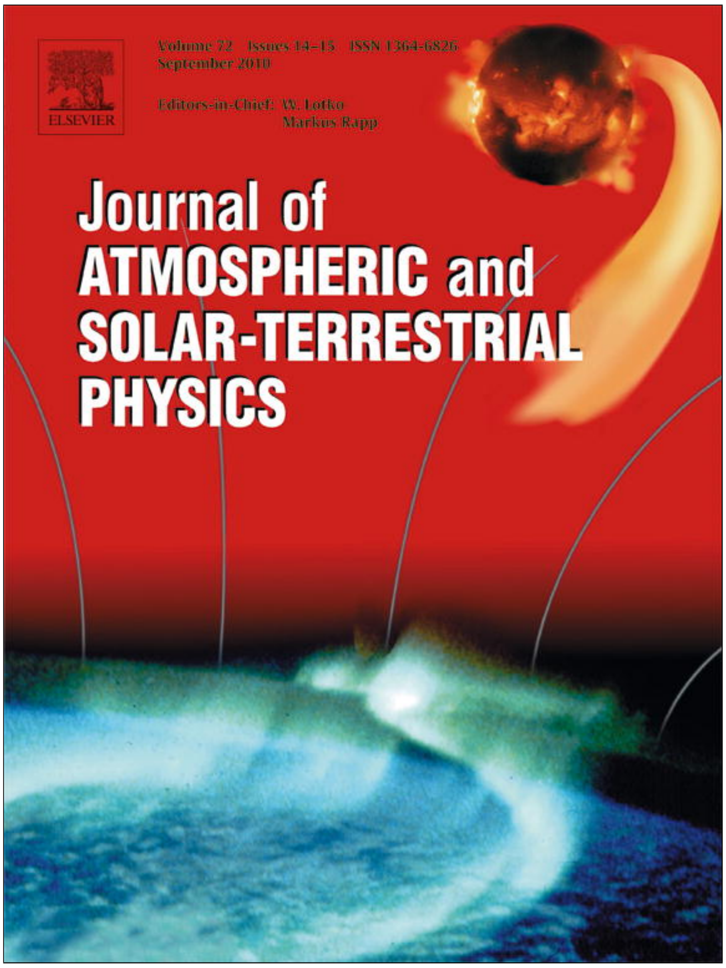
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Observations of noctilucent clouds from Lithuania

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ABSTRACT

We present an analysis of systematic visual and photographic observations of noctilucent clouds seen from Lithuania in the years 1973–2009. The main trends in the noctilucent cloud occurrence frequency and the mean brightness are derived from statistical and correlation analysis. A clear signature of the solar activity cycle is imprinted on the noctilucent cloud occurrence frequency and mean brightness, both showing distinct anti-correlation with the sunspot numbers; however, no statistically significant increase of either noctilucent cloud occurrence frequency or brightness has been detected at least over past 19 yr (1991–2009). The only statistically significant positive trend is established for the numbers of very bright noctilucent cloud displays in the years 1973–2009. The most recent noctilucent cloud observations are linked to variations of local mesospheric temperatures, measured by the Aura satellite.

1. Introduction

Noctilucent clouds (NLCs) are the highest clouds in the atmosphere, occurring during summer months at the vicinity of the polar mesopause. These clouds are composed of ice crystals and occupy a narrow layer at the altitude of 80–85 km. In the northern hemisphere NLCs are viewed from mid-to-high latitudes ($50-70^{\circ}$) during short summer nights as transparent patchy structures, which stand out clearly against the twilight sky (Fig. 1). Discovered in 1885, NLCs constitute the newest optical phenomenon in the atmosphere and attract continuous scientific attention throughout many years (Fogle and Haurwitz, 1966; Gadsden, 1982; Gadsden and Schröder, 1989; Thomas, 1991). The origin of the unexpected appearance, climatology and composition of NLCs has remained a hot debated topic for almost a century. It was until 1967, when formation of NLCs has been related to extremely low temperatures of the summer mesopause (Theon et al., 1967). In 1972, Donahue et al. (1972) using satellite data, discovered an extended mesospheric cloud layer above the entire polar regions, which was termed polar mesospheric clouds (PMCs). In this regard, NLCs are considered as a visible edge of the PMCs. In 1989, the formation of the NLCs has been linked to the increased concentrations of the mesospheric water vapor, which in turn was directly related to the increased methane emissions of anthropogenic origin and subsequent oxidation processes (Thomas et al., 1989). Under extreme ambient conditions ($T<145$ K) that occur at the vicinity of the summer mesopause, water vapor condensation process starts at ~ 90 km height with ions and meteoric dust particles serving as condensation nuclei. The sharp inhomogeneities in the electron density (about 3 m for a 50 MHz radar) produced by a few-nanometer size charged crystals give rise to a phenomenon, known as polar mesospheric summer echoes (PMSE)—strong back-scattering of very high frequency (VHF) radio waves (Rapp and Lübken, 2004). As the ice crystals grow in size, they fall down acquiring an average dimension of ~ 50 nm, that is sufficient to scatter the visible light (Kokhanovsky, 2005). The scattering is most efficient for the shortest visible wavelengths, and combined with the ozone absorption, yields a characteristic pale blue color of NLCs. It is interesting to note that water ice as the main constituent of NLCs was proved only recently from satellite-based infrared spectral measurements (Hervig et al., 2001).

In recent years the growth of interest in NLCs has been accelerated due to their possible connection with the global climate change in the upper and middle atmosphere, which might reflect to greater extent the global changes occurring near the surface (Thomas and Olivero, 2001; Thomas, 2003). From this point of view, long-term trends in the NLC occurrence frequency and variations in their brightness (or albedo) in particular, might serve as a primary indicator for tracking the global changes in the atmospheric environment. Indeed, recent studies revealed a significant secular increase of the PMC occurrence frequency and brightness (albedo) since 1979, when the satellite-based measurements became available (DeLand et al., 2003, 2006, 2007; Shettle et al., 2009). In the northern hemisphere, strong positive trends are detected for high latitudes ($64-82^{\circ}$), while for lower latitudes ($50-64^{\circ}$), where NLCs could be observed, the trends are considerably smaller, as recently found by Shettle et al. (2009),

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Fig. 1. (Color online) Noctilucent clouds over Lithuania. Photograph taken by A. Dubietis from Salakas (55°35′N, 26°08′E) on the night of 29/30 June, 2007.

possibly due to latitudinal dependence of the gravity wave activity (Thayer et al., 2003) and of the mesopause temperature. Recently, Bremer et al. (2009) reported positive trends in polar and mid-latitude mesosphere summer echoes from the VHF radar data analysis over shorter time period (1994–2008). Concerning the trends in the mid-latitude NLC variability, positive long-term trends considering various aspects of the NLC occurrence frequency and brightness had been indeed detected using data collected from ground-based observations (Dalin et al., 2006a; Kirkwood et al., 2008); however, most of these trends are lacking statistical significance. In this regard, a significant effort was directed to detailed studies of the NLC climatology by coordinated ground-based visual observations in Europe (Gadsden, 1998; Romejko et al., 2003; Dalin et al., 2006a; Kirkwood et al., 2008) and in North America (Lohvinenko and Zalcik, 1991; Taylor et al., 2002), in the range of 55–60° northern latitude, where the most favorable geometrical conditions (illumination of the twilight arch and the duration of twilight) for NLC observations occur. These studies had disclosed that a variability of the NLC occurrence rates is driven by solar-terrestrial interactions (e.g. solar activity, and high and middle atmosphere dynamics), being anti-correlated with the solar activity cycle; however, many issues concerning the suspected long-term change in NLC observational characteristics still remain open. Recent investigations also revealed that the observations carried out from compact geographical sites are of utmost importance for precise and reliable definition of the long-term trends, as clearly outlined by Kirkwood et al. (2008). Moreover, the major benefit of a compact geographical location is that such data provide a valuable information on atmospheric conditions, which are related to quasi-stationary and stationary processes, such as mountain gravity waves and stationary planetary waves, with certain orographic properties intrinsic to a given location on the Earth. Another important benefit of a compact location is that such observations are performed by the same qualified observers and with the same observing technique throughout the years, and therefore the observations are validated and well-calibrated.

In this paper we present the statistical analysis of NLC observations from Lithuania, collected in the years 1973–2009. We derive the main trends in the NLC climatology and compare our results with those recently obtained from compact European sites (Moscow, Denmark and the United Kingdom) located close to 56° northern latitude circle, where local mesospheric conditions are expected to be very similar.

2. Lithuanian NLC database

The Lithuanian NLC database contains 480 NLC reports collected in the years 1973–2009, which reveal 371 distinct cases

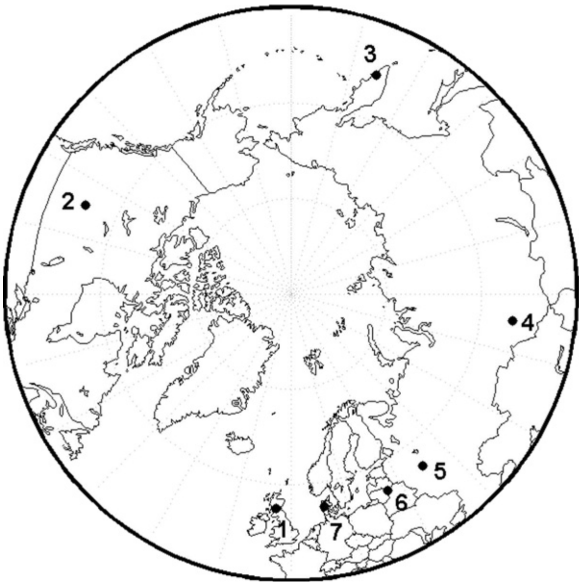

Fig. 2. A map of the ground-based photographic network for NLC observations: 1—Port Glasgow (UK), 2—Athabasca (Canada), 3—Kamchatka, 4—Novosibirsk, 5—Moscow (all Russia), 6—Salakas, Vilnius and Vidiškes (average location, Lithuania), 7—Aarhus (Denmark).

of NLC occurrence. In the time period of 1973–1990 only the brightest NLC displays were recorded by visual means, while starting from 1991, visual and photographic NLC observations were performed on a regular basis from 20 May to 15 August. The full data description includes date and time of the observation, weather conditions (tropospheric cloud coverage), time of the beginning and the end of NLC visibility, their maximum brightness on a five-point scale and the morphological forms present. All the observations were carried out from Eastern Lithuania, mainly from the three sites: Vilnius (54°48′N, 25°48′E), Vidiškės (55°22′N, 26°12′E) and Salakas (55°35′N, 26°08′E). Since 2008, the observations were performed on sole photographic basis, with two automated digital photo cameras as a part of the world-wide ground-based photographic NLC network (Dalin et al., 2008). A map showing the location of the Lithuanian sites relative to other NLC observing sites within the ground-based photographic NLC network is presented in Fig. 2. Besides the general information on the NLC statistics, photographic observations enable precise studies of short-term variability of NLC brightness, direction and speed of mesospheric winds and dynamic effects, such as wave motion, Kelvin–Helmholtz instabilities, etc. in the course of the night with 1 min temporal resolution (Dalin et al., 2010a). Moreover, the distance between the two cameras located in Salakas and Vidiškės is ~40 km, therefore allowing for accurate retrieval of three-dimensional NLC images.

3. Period of visibility

The general NLC statistics summarizing the observations in the years 1991–2009 is depicted in Fig. 3 and is contributed by the overall number of 343 distinct NLC cases. The histogram in Fig. 3(a) shows the summary of distribution of day-by-day NLC sightings. Fig. 3(b) shows the NLC sighting probability on a clear night, that is the number of observed NLCs divided by the number of clear nights in the corresponding time interval. The NLC sighting probability is calculated as 5-day averages, which suppress a spiky character due to the limited number of observations, and still maintains a reasonable temporal resolution. The NLC sighting probability has nearly Gaussian distribution (as seen

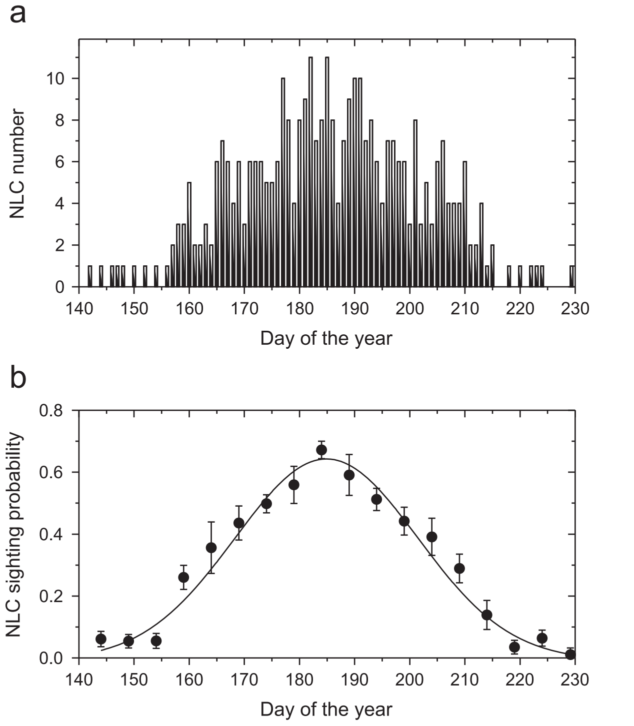

Fig. 3. General NLC observing statistics throughout the entire NLC formation season in the years 1991–2009: (a) number of nights with NLCs present, (b) NLC sighting probability on a clear night, derived as 5-day averages. The curve shows a Gaussian fit.

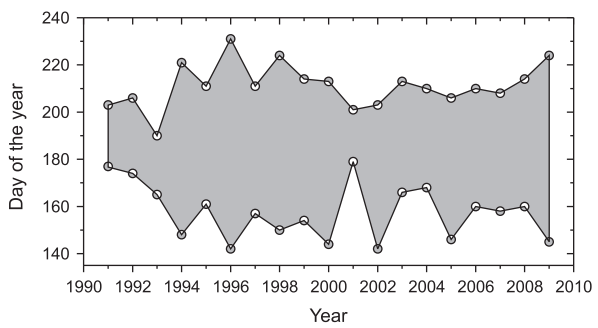

Fig. 4. NLC visibility season in the years 1991–2009.

from a Gaussian fit) and peaks on a first week of July. The so-called "peak NLC season" is defined by a sighting probability of ≥ 0.45, which marks the time period of intense formation of NLCs, and which extends from 15 June to 20 July.

The statistically averaged NLC observing season (with nonzero sighting probability) lasts for 85 days, from 22 May to 15 August, whereas its particular duration varies significantly from year to year, as illustrated in Fig. 4. In part, the estimated length of the NLC season (a time period between the first and the last NLC sighting) is slightly biased by local weather conditions: according to local weather records, the number of clear and semiclear nights in Lithuania, allowing for observations, varies from 50% to 80% during the NLC observing season.

However, more generally, the NLC season is intimately linked to the length of the summer season in the mesosphere, as indicated by seasonal drop of mesospheric temperatures (Kirkwood et al., 2008). Therefore it is interesting to link the individual NLC occurrences with the local environmental conditions in the mesosphere. The environmental data (temperature and amount of water vapor around the mesopause) were provided by the Microwave Limb Sounder (MLS) on the Aura satellite, operating with near-polar, sun-synchronous orbit at 705 km height, and which continuously measures relevant parameters of the Earth's atmosphere (Waters et al., 2006). The Aura MLS version 2.2 data were obtained from the NASA public web-site: http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/MLS/ml2t.002.shtml. The MLS temperature and water vapor data sets have been selected for the height of the mesopause (around 85 km), at a longitude closest to the longitude of Vilnius at a 60° latitude circle (referring to the central portion of the NLC field in terms of a distance from the observer), and for the nighttime part of the orbit, which is close to local nighttime conditions of observing NLCs. The MLS data have been used without any interpolating and filtering procedures for comparing to NLC displays seen from Lithuania. The temperature vertical resolution at mid-latitudes at 85 km height is 12–14 km, with the sampling interval of 1.5° in latitude and 24.5° in longitude due to widely spaced orbit tracks. Also, there exists a relatively large horizontal footprint (12×200 km) of the MLS data. The validation on the Aura MLS temperature data could be found in Schwartz and et al. (2008). The estimation of the frost point temperature was based on a formula presented by Gadsden and Schröder (1989). The detailed comparison of the MLS data and NLC observations around the globe is presented by Dalin et al. (2010b).

A connection between the NLC occurrences and the mesospheric temperature in 2007 and 2008 is illustrated in Fig. 5. Despite limited vertical and horizontal resolution, Aura data provide quite accurate estimation of local conditions,

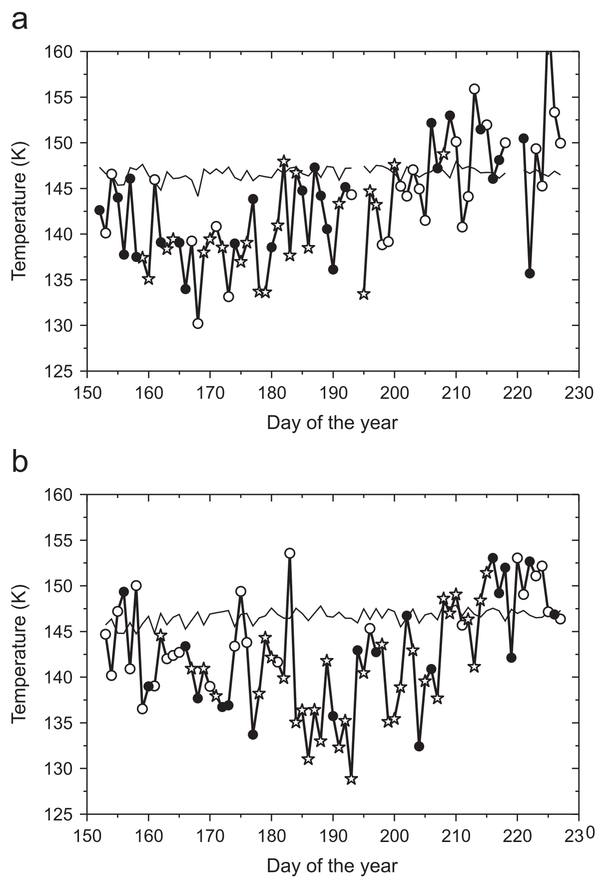

Fig. 5. Day-by-day NLC occurrences, temperature of the mesopause (bold curve) and frost point temperature (thin curve) at $h=85$ km from Aura satellite measurements (a) in 2007 and (b) in 2008. Nights with NLCs present are indicated by stars, while open and full circles show clear-semiclear nights without NLCs and cloudy nights, respectively. The data range in the plot covers the time interval from 1 June to 15 August.

especially in the case of extended, large area NLC displays. Note, how most of the NLC occurrences are linked with the drop of the mesopause temperature below the frost point, calculated based on the amount of water vapor. Gaps in Fig. 5(a) are due to the Aura data voids. At the same time, there is a number of NLC cases when the mesopause temperatures are above the frost point temperature. In part, this fact may be explained by spatial variations in temperature between grid point temperatures, since the Aura spatial resolution in longitude is poor (24.5°). Indeed, it is very possible that local temperature structures are small enough and therefore could not be resolved by present satellite measurements. On the other hand, the possibility of NLC formation in above-frost-point conditions could not be completely ruled out, as inferred by the discovery of existence of PMCs in unsaturated air (Stevens et al., 2001).

It is interesting to mention two marginal out-of-season NLC sightings in 2000 by experienced observer R. Balčiūnas on the nights of March 29/30 and April 27/28. These extreme cases are not alone in the NLC statistics; for example, high-latitude out-of-season NLC observations were reported by Lohvinenko and Zalcik (1991) on 10 September 1988, from Cape Parry, Canada (70.2°N) and by Warren et al. (1997) from the South Pole on 29 April 1992, as late as four months after summer solstice. The exact geophysical causes for these unexpected NLC formations had not been identified and still remain unclear, but these might be attributed either to the formation of unusually cold pockets of air, for instance, due to gravity wave breaking, or to large amounts of water vapor release from a Space Shuttle or large rocket launch (Stevens et al., 2005).

4. NLCs and solar activity

The available observations of very bright NLCs date back to 1973, with the total amount of 96 very bright NLC displays, recorded in 37 yr period, that extends almost for four solar activity cycles. Out of these, 16 NLC displays were classified as exceptionally bright, according to a brightness scale provided in Section 5.2 of the paper. Data from years 1991–2009 provide a total number of year-by-year NLC occurrences, including also moderate and faint NLC displays. The total number of NLC sightings (that is the number of nights with NLCs present) in the years 1991–2009 amounts to 343 cases, with the highest NLC numbers observed in the years 1994 and 2008–2009, which count more than 30 NLC occurrences during the observing season, while the lowest NLC formation activity was recorded in the years 1991–1993 and 2001–2003 with 5–12 NLC cases per year. The summary of the above results is illustrated in Fig. 6 by plotting year-by-year NLC numbers along with variations of the solar activity, expressed by monthly averaged international sunspot numbers R_i. The time series of the international sunspot numbers are provided by the Solar Influences Data Analysis Center (SIDC) at http://sidc.oma.be/sunspot-data/.

A raw comparison of the plots in Figs. 6(a) and (b) suggests that the number of very bright NLC displays increases markedly in the years of the sunspot minima, while they are rare or completely absent in the years associated with the sunspot maxima. The same character of variability holds also for the number of total NLC sightings. In order to investigate this relationship in a more precise manner, we have performed a correlation analysis, which involved the calculation of the cross-correlation function between the NLC numbers, N_{NLC}, and June–July averages of the sunspot numbers R_i

$$\mathrm{cc}(l) = \frac{\overline{(N_{\mathrm{NLC}}(t) - \overline{N_{\mathrm{NLC}}})(R_i(t+l) - \overline{R_i})}}{\sqrt{\sigma(N_{\mathrm{NLC}})\sigma(R_i)}}, \qquad (1)$$

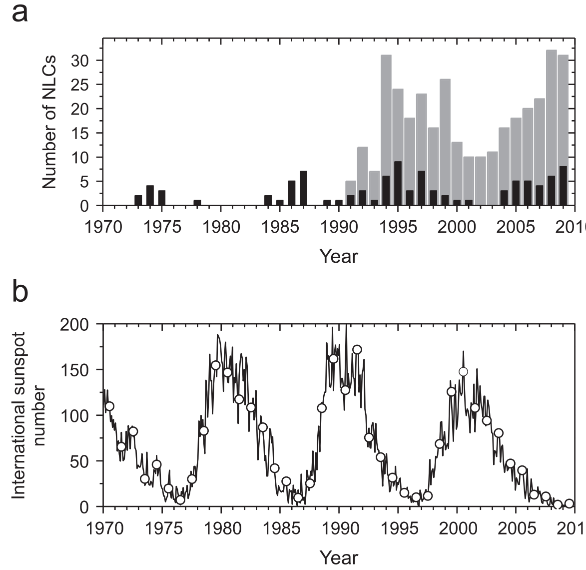

Fig. 6. (a) NLC occurrence statistics. Gray bars—total number of nights with NLCs visible, black bars—number of very bright NLC displays. (b) Solar activity, expressed in monthly averaged international sunspot numbers. Open circles indicate June–July averages of the sunspot numbers used for correlation analysis.

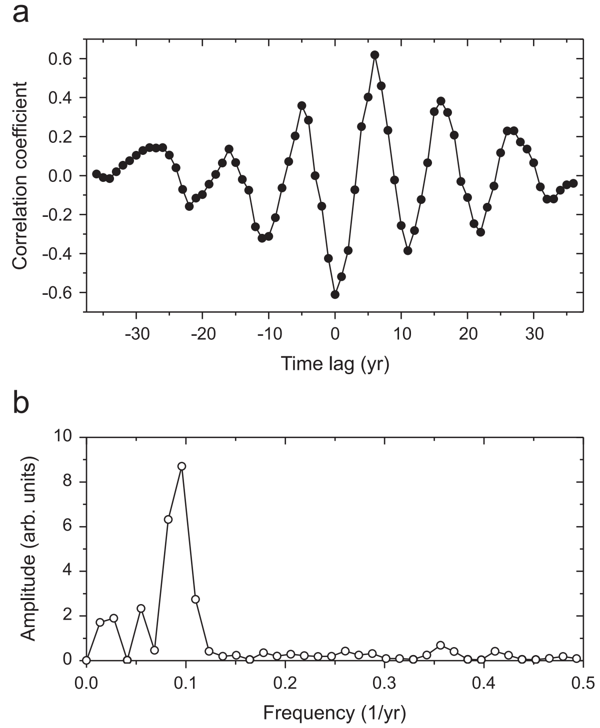

Fig. 7. (a) Cross-correlation function between the numbers of very bright NLCs and averaged sunspot numbers in June–July. (b) Frequency spectrum of the cross-correlation function.

where t is time (in years), l is the time lag, the overline operators denote time averages, $\sigma(N_{\mathrm{NLC}})$ and $\sigma(R_i)$ are the variances of time series of NLC numbers and sunspot numbers, respectively.

The cross-correlation function between very bright NLC displays and sunspot numbers is depicted in Fig. 7(a), whose values fall into the range between −0.63 and +0.61, showing distinct anti-correlation between the variables of interest. The cross-correlation curve reveals several important features: (i) the peak of negative cross-correlation coefficient coincides with a 0 time lag, while the peak of positive cross-correlation coefficient is shifted by $\sim 5-6$ yr, indicating that the variables of interest are anti-correlated; (ii) periodic oscillations of the cross-correlation coefficient occur on a ~ 10 yr time scale. More precisely, the period of the oscillations was evaluated from the frequency spectrum, obtained by applying the Fourier transform. The frequency spectrum of the cross-correlation function is depicted in Fig. 7(b). A prominent peak in the Fourier spectrum suggests a period of $T = 10.4 \pm 0.6$ yr, which is fairly close to the average period of the solar cycle (~ 10.6 yr).

The cross-correlation function between the total NLC numbers and sunspot numbers is depicted in Fig. 8. The general result in terms of the correlation coefficient and its periodic variability is very similar to that obtained for very bright NLC displays; however, in the present case a 1–2 yr time shift between the minimum sunspot numbers and the maximum NLC numbers is clearly visible. The above results indicate high variability of the NLC occurrence frequency in the course of the solar cycle, with almost threefold increase of total NLCs numbers during periods of the sunspot minima. Indeed, it is well established that the NLC numbers vary periodically in response to the solar activity cycle (Gadsden, 1998; Romejko et al., 2003): the most frequently NLCs are observed during the years of sunspot minima, with some 1–2 yr time delay. The fundamental reason for this variability is generally attributed to the increase or decrease of the solar radiation fluence mainly in the vacuum ultraviolet (VUV) spectral range (100–200 nm) that is responsible for variations of water vapor mixing ratio (Sonnemann and Grygalashvyly, 2005) and to some extent for the heating of the mesospheric environment (Lean, 1997). The observed 1–2 yr time delay still misses a reasonable explanation, although by now it is considered as due to a delayed complex response of the overall atmospheric circulation (Kirkwood et al., 2008).

We have also examined the variability of mean NLC brightness in the course of the solar cycle by means of the correlation technique as described above. We have found that variability of the mean NLC brightness holds a very similar character as derived for NLC numbers. Specifically, the cross-correlation function (not shown here) between the mean NLC brightness (its derivation is discussed in detail in Section 5.2) and the sunspot numbers shows that brighter NLCs are observed in the years of the sunspot minimum (with no time shift), and the correlation coefficients range from -0.37 in the years of the sunspot minimum to +0.44 in the years of the sunspot maximum.

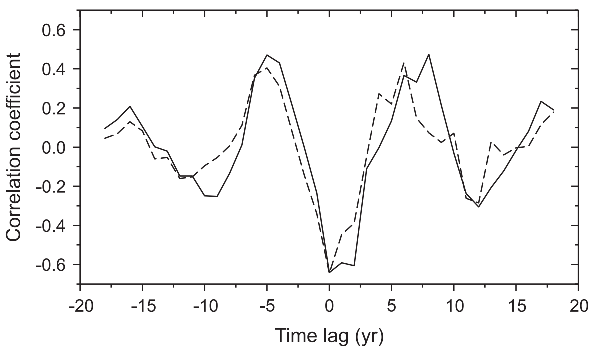

Fig. 8. Cross-correlation function between the total NLC numbers as observed in the years 1991–2009 and the sunspot numbers (solid curve). The cross-correlation for very bright NLCs and sunspot numbers (dashed curve) is calculated for the same time interval and is shown for a comparison.

5. Trends in NLC characteristics

5.1. NLC occurrence frequency

In the preceding section we have shown that the observed NLC numbers are strongly influenced by the solar activity, as indicated by the correlation analysis. In order to retrieve the long-term trends, it is thus necessary to subtract the variable component related to solar activity. For this purpose we have performed a multiple linear regression analysis. The time series of the observations were fitted by the following equation:

$$N = A_0 + A_1(year - T_s) + A_2 R_i, \quad (2)$$

where A_0 is the constant, A_1 and A_2 are the regression coefficients for the time trend and for the sunspot numbers, respectively, and T_s is the start year of the time series. In the case of very bright NLCs, no time shift between the appropriate time series was applied, as inferred by correlation analysis. Fig. 9 summarizes the main results obtained for very bright NLC displays. Fig. 9(a) compares the time series of the observed very bright NLC displays with the time series of those derived from the multiple linear regression, which yielded following relevant coefficients: $A_0 = 3.025 \pm 0.767$, $A_1 = 0.081 \pm 0.029$ and $A_2 = -0.029 \pm 0.006$. In Fig. 9(b) we plot the corrected number of very bright NLC displays, N_{corr} after subtraction of the solar component, which was calculated as

$$N_{corr} = N_{obs} - A_2 R_i, \quad (3)$$

where N_{obs} denotes the observed value. The linear fit shows a marked increase of the number of very bright NLC displays, indicating that it has almost doubled in the period from 1973 to 2009, and suggests that this result should be regarded as highly statistically significant.

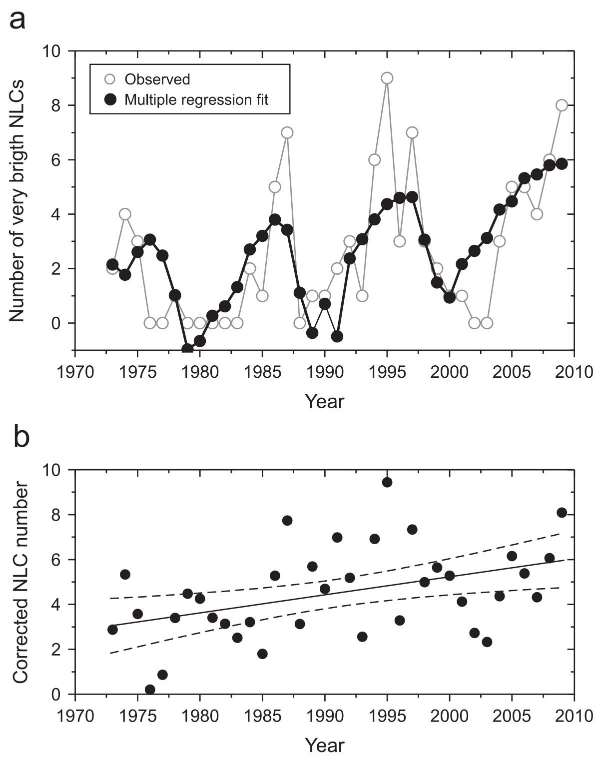

Fig. 9. (a) Time series of very bright NLC displays: observational data (open circles and gray curve) and data obtained from multiple linear regression fit (full circles and bold line). (b) Long-term trend in very bright NLC displays after subtraction of the solar component. Solid line shows linear fit, dashed curves denote 95% confidence limit.

Next we performed the same procedure for the time series of the total NLC numbers in the time period of 1991–2009. Here we apply +1 yr time shift for the sunspot time series, as found from the cross-correlation data presented in Fig. 8. Prior to calculation of multiple linear regression coefficients, we also applied a correction for weather conditions with account for the NLC sighting probability, as specified in Fig. 3(b). Hence, we recalculate a "weather-corrected" NLC number for a particular year as

$$N^*_{\mathrm{NLC}} = N_{\mathrm{NLC}} + \sum N_{\mathrm{cloudy}}(\Delta t)p(\Delta t), \tag{4}$$

where $N_{\mathrm{cloudy}}(\Delta t)$ and $p(\Delta t)$ denote the number of cloudy nights and NLC sighting probability for a particular 5-day interval, respectively. The multiple linear regression fitting procedure yielded the following set of relevant parameters: $A_0 = 32.67 \pm 2.84$, $A_1 = 0.166 \pm 0.198$ and $A_2 = -0.088 \pm 0.021$. The results are summarized in Fig. 10. Fig. 10(a) compares the observed, "weather-corrected" and derived from multiple linear regression NLC numbers. The trend in overall NLC numbers after subtraction of the solar component (referred as corrected NLC numbers) in 1991–2009 is depicted in Fig. 10(b) and is weakly positive (showing 10% increase over 19 yr), but of low statistical significance, as indicated by wide 95% confidence margins. On the other hand, we note that even after correction for weather conditions and subtraction of the solar component, quite significant variations of the corrected NLC numbers are still present, which might be resulted by the complex interplay of other, including geophysical, still unidentified factors.

5.2. NLC brightness

Brightness is one of the main factors characterizing the NLC dynamics on different time scales in response to local and global conditions that occur in the mesosphere. Local and short-lived changes in the mesosphere are driven by the complex interplay between the atmospheric tides, gravity (buoyancy) waves and planetary waves, and NLCs at mid-latitudes of 55–60°N exhibit distinct variations on a 2, 5 and 16-day scale (Kirkwood et al., 2008; Dalin et al., 2006b, 2008). The global changes, on the other hand, are imposed by the long-term variability sources such as solar activity, and, more importantly, supposed as due to the global changes in the mesospheric temperature, water vapor concentration, etc. driven by anthropogenic activities, such as greenhouse gas emissions, and therefore may be linked to global climate change.

The NLC brightness could be estimated using different techniques. Instrumental estimations of the NLC brightness (e.g. albedo measurements or photometric observations) could be precisely calibrated, while visual estimations of apparent NLC brightness are considered to be much less precise and hence far less useful. Indeed, NLC brightness estimations from visual observations collected from extended observing networks encounter problems with the accuracy as due to particular observing conditions for a given location and individual observer biases, as well as due to finite extension of the NLC field (~800 km on the average, as estimated from mid-latitude NLC observations Dalin et al., 2006a). Nevertheless, visual brightness estimations from compact geographical locations, especially if carried out by experienced observers using a well-established methodology, might provide a set of reliable data.

In visual observations, the NLC brightness is estimated using a five-point scale according to Fogle and Haurwitz (1966): 1—barely visible, 2—faint, 3—moderate, clearly standing out against the background of a twilight sky, 4—very bright, attracting attention of casual observers, 5—exceptionally bright, that illuminate objects. This division might seem to be very approximate, however, experienced observers could estimate the NLC brightness with precision of 0.5 point, regardless on viewing conditions (atmospheric haze, partial tropospheric cloud coverage, presence of moonlight, etc.). Indeed, the Lithuanian data on the NLC brightness is provided just by two observers (A. Dubietis and R. Balčiūnas), whose brightness estimations coincide to a high degree: more than 80% of independent brightness estimates lie within ±0.5 point margin, as verified by 69 simultaneous observations of the NLC displays, see Fig. 11. The highest discrepancies ≥ ±1.0 were found when either comparing individual brightness estimates from two distant locations, e.g. Vidiškes and Vilnius (separated by a distance of ~100 km) or in presence of considerable tropospheric cloudiness.

In what follows, we calculate the mean NLC brightness as yearly averages of the peak NLC brightness recorded overnight. The peak NLC brightness is estimated as a brightest part of the

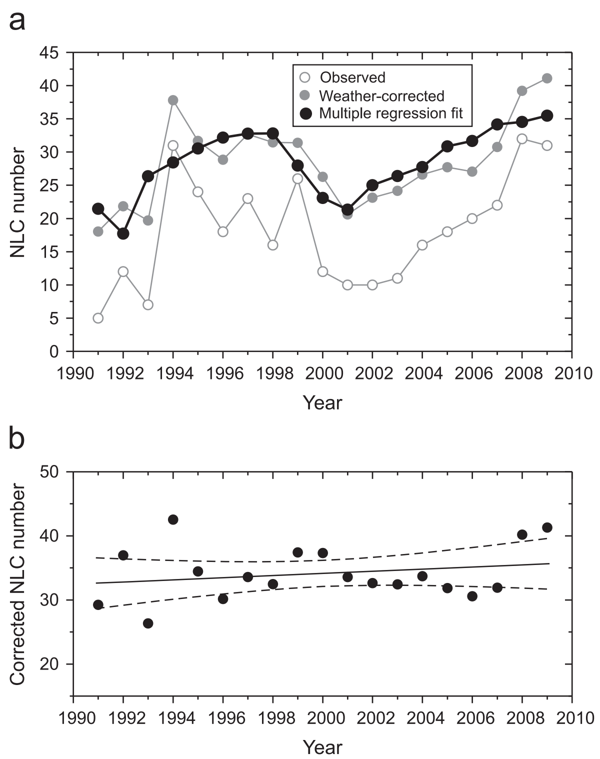

Fig. 10. (a) Time series of the overall NLC sightings: observational data (open circles and gray curve), "weather-corrected" NLC numbers (full circles and gray curve) and NLC numbers obtained from multiple linear regression fit (full circles and bold curve). (b) Long-term trend in corrected NLC numbers after subtraction of the solar component. Solid line shows linear fit, dashed curves denote 95% confidence limit.

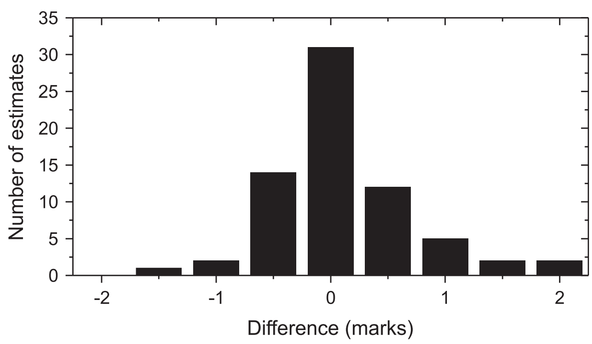

Fig. 11. Differences of the individual NLC brightness estimates from 69 simultaneous observations.

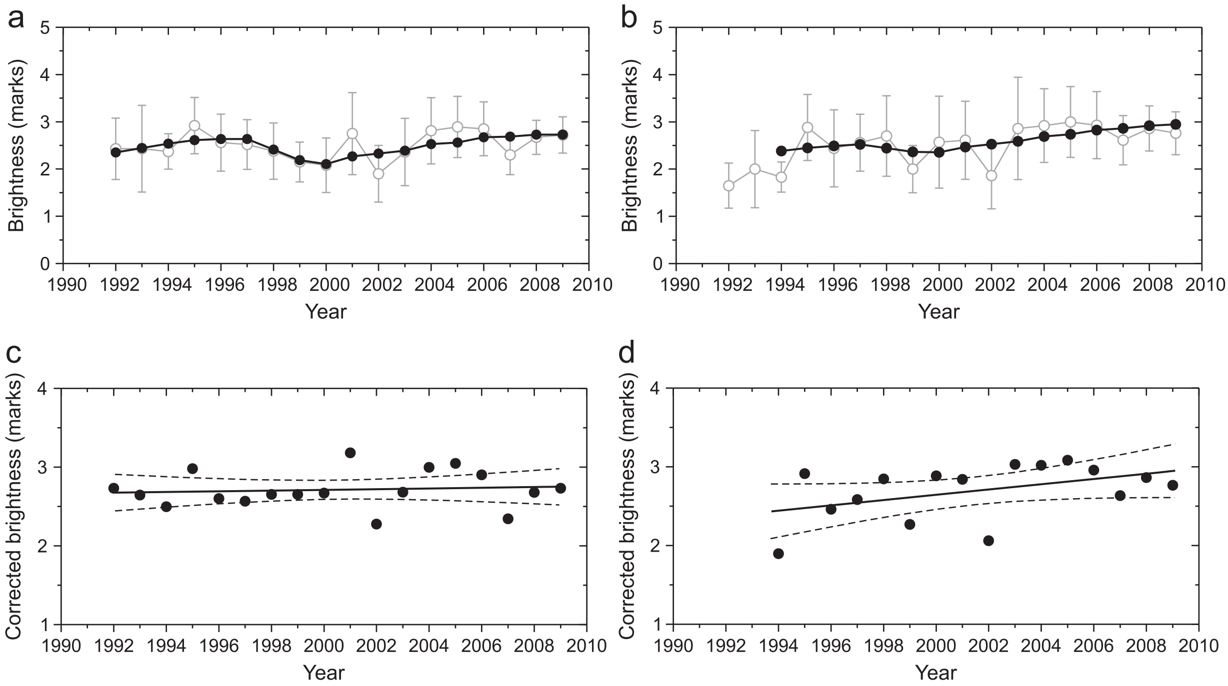

Fig. 12. Time series of mean NLC brightness in 1992–2009 as derived for (a) whole NLC sighting period, (b) "peak NLC season". Open circles and gray curves depict the observational data from visual estimations, full circles and black curves show the data from multiple regression fits. (c) and (d) show the corrected respective values after subtraction of the solar component. Solid lines show linear fit, dashed curves show 95% confidence limit.

NLC field during the night, and then these estimates are averaged to obtain the mean NLC brightness for a given year. Since the observations are carried out within limited intervals of time (usually 15 min), fast transient changes of the NLC brightness are usually "smoothed". Fig. 12(a) illustrates the time series of the mean NLC brightness for the whole NLC sighting period (effectively, from 22 May to 14 August), while Fig. 12(b) plots the mean NLC brightness for the "peak season", i.e. from 15 June to 20 July. The error bars in both plots were defined according to Poissonian distribution. The results are further analyzed by means of a multiple linear regression procedure, as described in detail in the preceding section. In Figs. 12(a) and (b), the corresponding multiple regression fits (full circles and bold curves) are superimposed on the observational data. The multiple linear fits yielded the following coefficient sets $A_0=2.655\pm0.147$, $A_1=0.005\pm0.116$, $A_2=-0.004\pm0.001$ and $A_0=2.444\pm0.205$, $A_1=0.033\pm0.019$, $A_2=-0.002\pm0.002$, for the whole NLC sighting period and for the "peak season", respectively.

Figs. 12(c) and (d) show the time series of the NLC brightness after subtraction of the solar component (referred as corrected NLC brightness). The variation of the NLC brightness estimated for the whole sighting period shows an indistinguishable from zero trend, as indicated by the linear fit in Fig. 12(c), with the mean NLC brightness oscillating around $\sim$2.65 in 1992–2009. Concerning the corrected NLC brightness during the "peak season", its trend was established for the time period 1994–2009, excluding data points from years 1992 and 1993, whose values fall markedly below the average, as well as below the averages estimated for the whole NLC sighting period. A closer look revealed that these data points coincide with relatively short NLC visibility seasons in 1992 and 1993 (see Fig. 4), which even only partially overlap with the peak NLC season due to extended periods of bad weather in these years. The obtained trend is apparently positive, showing an increase of mean NLC brightness by $\sim$0.5 mark in 16 yr, as illustrated in Fig. 12(d), however its statistical significance is only marginal.

6. Discussion

It is interesting to compare the results of the Lithuanian NLC database with the results obtained from other compact European sites located on 55–56°N latitude circle: the UK, Denmark and Moscow (see Fig. 2), those data are analyzed in detail by Romejko et al. (2003), Dalin et al. (2006a) and Kirkwood et al. (2008). A distinct anti-correlation between the NLC numbers and solar activity has been unambiguously established by Gadsden (1998) from combined North–West European visual NLC observations in 1964–1995. Recently, more thorough investigations have been carried out considering observational data from compact geographical regions, restricted both in latitude and longitude. Romejko et al. (2003) analyzed Moscow data from 1962–2001 and concluded that both NLC characteristics, i.e. NLC numbers and integral brightness (that is the sum of the brightness values estimated in every 15 min interval), vary almost in anti-phase with the 10.7 cm solar radio flux, taken as a measure of the solar activity. They also established that the maximum NLC occurrence rates and seasonally averaged integral brightness are lagged at about 1 yr after the minimum of the solar activity, and the variability period is 9.4 ± 0.2 yr, that is $\sim$1 yr shorter than the period of the solar activity. Dalin et al. (2006a) found a very similar NLC variability parameters from Moscow and Danish NLC data from 1962 to 2005 and 1983 to 2005, respectively, comparing NLC activity and solar Lyman-α radiation at 121.6 nm. These authors also concluded that a shorter NLC variability period may lead to a slowly moving lag between the maximum of the NLC activity and the minimum of the solar activity, which may vary from 0 to 3 yr. Kirkwood et al. (2008) analyzed NLC number variability from combined Danish and UK observations in 1964–2006. These authors obtained a variability period for NLC displays of moderate or greater brightness (excluding the fainter ones) of 10.2 ± 0.8 yr and a time shift of 13–17 months as compared to variations of the 10.7 cm solar radio flux.

The NLC variability analysis of the Lithuanian NLC database has been performed by linking relevant NLC characteristics to the International sunspot numbers. The present results show that the NLC numbers vary in the course of the solar cycle with moderate degree (0.6) of anti-correlation between the observed NLC numbers and the international sunspot numbers. In particular, a distinct anti-correlation is found for very bright NLC displays in 1973–2009 (with 0 time lag) and for total NLC numbers in 1991–2009 (with 1–2 yr lag). The NLC variability period is established only for very bright NLC displays in 1973–2009 and equals to 10.4 ± 0.6 yr, as found from the Fourier spectrum. This result almost perfectly coincides with the value of 10.2 yr found from the Danish and UK observations (Kirkwood et al., 2008) and slightly differs from that of 9.4 yr of the Moscow database (Romejko et al., 2003; Dalin et al., 2006a). The latter difference might be attributed to somewhat different time period covered by the Moscow observations (from 1961 to 2001) taking into account that the solar cycle is variable in its length as well.

The analysis of the Lithuanian data concerning the variability of the NLC brightness revealed that the mean NLC brightness evaluated for the entire and for the "peak" NLC visibility season in 1992–2009, anti-correlates with the international sunspot numbers, although to a lesser degree (the correlation coefficient is ~ 0.4) as compared to NLC numbers. The correlation function yields a 0 time lag, but this also might be an artefact of a short data set. This result in general agrees with the results of Moscow and Danish databases (Romejko et al., 2003; Dalin et al., 2006a), although these were analyzed in a slightly different aspect, i.e. considering the integral NLC brightness, which accounts also for the length of a particular NLC display.

As far as concerning the long-term trends in the NLC variability at mid-latitudes (UK, Danish and Moscow databases), positive trends in the NLC occurrence frequency and brightness had been indeed detected, however, most of them lacking statistical significance. In particular, Dalin et al. (2006a) found positive trends in the NLC frequency and brightness from Moscow and Danish observations in the time period of 1983–2005, while only the trends for a latter location were statistically significant. The authors also showed that combining of Moscow and Danish data sets improves the statistical significance of the obtained trends. Analysis of longer (1962–2005) Moscow data set yielded a positive trend in the NLC brightness and nearly zero trend in the NLC occurrence frequency, both with low statistical significance. Kirkwood et al. (2008) analyzed long-term trends in the NLC occurrence frequency from combined UK–Denmark records in 1964–2006. The authors investigated the NLC occurrence frequency in terms of numbers of bright and moderate NLCs, and overall NLCs (including faint and very faint displays). The both trends were found to be positive, but just the latter one was strong (showing a considerable increase of the occurrence rate at 0.4 nights per year) and statistically significant. However, the authors argued that this strong trend might be an artefact of observing practices (increasing skill in identifying faint NLCs) rather than a geophysical effect.

The Lithuanian NLC data were analyzed by similar techniques (multiple linear regression) and provides fairly consistent results. Specifically, positive and statistically significant trend was found in the occurrence frequency of very bright NLC displays in the period of 1973–2009, showing a marked increase of the number of very bright NLC displays and indicating that it has almost doubled during the investigated time period. In the future, this result might be checked for consistency with other databases, since this aspect of the NLC variability has not been considered before. The trend in the overall NLC numbers in 1991–2009 was found weakly positive (showing 10% increase over 19 yr), but of low statistical significance. Positive, but statistically insignificant trends were also obtained for mean NLC brightness estimated for the entire NLC visibility season in 1992–2009 and for the "peak NLC season" in 1994–2009.

The obtained multiple linear regression coefficients are summarized in Table 1. To summarize the above, the Lithuanian results generally agree with those obtained from other compact European sites of very similar geographic latitude, namely: UK, Denmark and Moscow. Despite the diversity of the NLC parameters analyzed (NLC occurrence frequency, with NLC brightness discrimination at different levels, and NLC brightness, estimated as integral or mean values), slightly different epochs and length of the data sets, a similar character of trends in NLC occurrence frequency and brightness, suggests that the observed positive trends in NLC characteristics are induced by some real effect. On the other hand, the statistical significance of the obtained trends is a factor, which certainly has to be improved. The uncertainties in the trends obtained for all sites suggest that the actual trends might by masked by the uncertainties arising from the limitations of the observing techniques (although these are minimized either by applying corrections for weather conditions, or by combining the data from certain geographical regions); however, it is equally very possible that some still unidentified sources of the NLC variability should be clarified and accounted for.

And finally, it is interesting to mention, that despite the marked differences in local weather conditions, that lead to differences in the observed NLC numbers during a particular NLC observing season, weather-corrected NLC numbers match to a high degree: the UK–Denmark observations report an average of 28 NLC occurrences per year, the Moscow data set—just slightly < 28 (Kirkwood et al., 2008), and the Lithuanian data set yields almost identical value of an average NLC occurrence rate as 28.4 NLC cases per year. This fact demonstrates the reliability of the Lithuanian NLC database and its consistency with existing databases, opening good perspectives for future investigations of the NLC characteristics across the whole Europe on $55-56^{\circ}$N latitude circle.

Table 1
Relevant parameters of the multiple linear regression fits.

NLC numbers	Year range	A_0, number	A_1, number/year	A_2, number/R_i	Lag	R^2
Overall	1991–2009	32.67 ± 2.84	0.166 ± 0.198	-0.088 ± 0.021	1.0	0.60
Very bright	1973–2009	3.025 ± 0.767	0.081 ± 0.029	-0.029 ± 0.006	0.0	0.51
NLC brightness	Year range	A_0, mark	A_1, mark/year	A_2, mark/R_i	Lag	R^2
Full season	1992–2009	2.655 ± 0.147	0.005 ± 0.116	-0.004 ± 0.001	0.0	0.36
Peak season	1994–2009	2.444 ± 0.205	0.033 ± 0.019	-0.002 ± 0.002	0.0	0.30

A_0 is the constant, A_1 is the time trend coefficient, A_2 is the solar coefficient, Lag denotes the applied time lag (in years) between the corresponding time series, and R^2 stands for the fit error.

7. Conclusions

We have presented an analysis of systematic visual and photographic NLC observations from Lithuania in the years 1973–2009. We define the basic observational characteristics of the NLCs (the sighting probability, the visibility season and the relationship with the mesospheric temperature from the Aura satellite, MLS instrument), present the time series of the relevant parameters (the NLC occurrence frequency and the mean brightness) and derive their long-term trends.

By comparing day-by-day NLC occurrence statistics and data for local mesosphere and frost point temperature, we show that the NLC formation is linked to the mesopause temperature drop below the frost point temperature. However, few above-frost-point NLC observations should be pointed out, and further studies are necessary to unveil if these observations are of real geophysical origin or just related to uncertainties in temperature measurements. Extension of these studies with regard to broader geographical coverage, opens an interesting research line for the nearest future (Dalin et al., 2010b).

The correlation analysis demonstrated that the NLC numbers and NLC brightness show a distinct anti-correlation with the international sunspot numbers, used as a measure of the solar activity. It was found that the numbers of very bright NLCs and NLC brightness vary exactly in anti-phase with the sunspot numbers, whereas the maximum of the overall NLC numbers is lagged by 1–2 yr with respect to the sunspot minimum.

Positive trends, considering several aspects of the NLC variability, were derived by multiple linear regression analysis. Namely, the trends in numbers of very bright NLC displays in 1973–2009, in overall NLC numbers in 1991–2009, and in mean NLC brightness, examining NLC brightness for the whole NLC visibility period in 1992–2009 and for the "peak NLC season" (from 15 June to 20 July) in 1994–2009, had been obtained; however, only the trend in very bright NLC displays could be regarded as statistically significant.

Our findings are very much in line with the statistical results and long-term trends in the NLC climatology established since, from visual and photographic observations from the European sites of similar geographical latitudes, e.g. Moscow, Denmark and the United Kingdom (Romejko et al., 2003; Dalin et al., 2006a; Kirkwood et al., 2008). In particular, a remarkable agreement with the published data is obtained despite the differences in the length of data sets, techniques of observations, weather conditions, and perhaps, other local effects, which are responsible, for instance, for different NLC numbers recorded per season:

- a typical NLC season at $55-56^{\circ}$ northern latitude extends from 20 May to 15 August, with very few exceptions, with the maximum on the first week of July;
- a 1–2 yr shift between the maximum overall NLC numbers and the minimum of the solar activity (sunspot numbers, in our case) is clearly identified;
- the NLC variability period derived from the Lithuanian data (10.4 yr) almost perfectly coincides with that found from the Danish and UK observations (10.2 yr) and slightly differs from that of the Moscow database (9.3 yr). The latter difference might be attributed to somewhat different time period covered by the Moscow observations (from 1961 to 2001) taking into account that the solar cycle is variable in its length as well;
- positive trends in the NLC occurrence frequency and brightness are obtained, in good agreement with recently published results on mid-latitude NLCs, indicating also that the statistical significance of the trends is still an important issue to be improved.

Considering the above results, the Lithuanian NLC observations comprise a robust and reliable data set. Hence, the extension of the existing Moscow, Danish and UK independent databases with the present one, will enable to achieve an excellent geographical coverage for long and short-term NLC monitoring across the Europe on a $55-56^{\circ}$ northern latitude circle. Moreover, the most recent data are gathered by the automatic camera network, using unified observing procedures, that successfully solve uncertainty issues related to visual observing practices. It is therefore expected that such unified database will put a solid background for better understanding of the NLC variability and for monitoring of the long-term trends on a global scale, revealing a larger picture, which will help to identify relevant forcing mechanisms of this beautiful summer phenomenon.

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