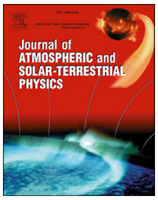
Journal of Atmospheric and Solar-Terrestrial Physics xxx (2017) 1–8

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp



Response of noctilucent cloud brightness to daily solar variations

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ARTICLE INFO

Keywords:
Noctilucent clouds
Polar mesospheric clouds
Summer mesopause
Solar activity

ABSTRACT

For the first time, long-term data sets of ground-based observations of noctilucent clouds (NLC) around the globe have been analyzed in order to investigate a response of NLC to solar UV irradiance variability on a day-to-day scale. NLC brightness has been considered versus variations of solar Lyman-alpha flux. We have found that day-to-day solar variability, whose effect is generally masked in the natural NLC variability, has a statistically significant effect when considering large statistics for more than ten years. Average increase in day-to-day solar Lyman-α flux results in average decrease in day-to-day NLC brightness that can be explained by robust physical mechanisms taking place in the summer mesosphere. Average time lags between variations of Lyman-α flux and NLC brightness are short (0–3 days), suggesting a dominant role of direct solar heating and of the dynamical mechanism compared to photodissociation of water vapor by solar Lyman-α flux. All found regularities are consistent between various ground-based NLC data sets collected at different locations around the globe and for various time intervals. Signatures of a 27-day periodicity seem to be present in the NLC brightness for individual summertime intervals; however, this oscillation cannot be unambiguously retrieved due to inevitable periods of tropospheric cloudiness.

1. Introduction

Noctilucent clouds (NLC) or the so-called night shining clouds are the highest clouds in the Earth's atmosphere formed and observed in summer time in the mesopause region between 80 and 90 km. NLC are composed of small water-ice crystals (~30–100 nm in radius) which effectively scatter sunlight, and hence these clouds are easily discernible against the twilight sky. NLC are observed from the end of May to September in the Northern Hemisphere and from the end of November to February in the Southern Hemisphere (Bronshten and Grishin, 1970; Gadsden and Schröder, 1989). NLC are also observed from space and in this case they are called Polar Mesospheric Clouds (PMC) (Thomas, 1984).

Atmospheric dynamics plays a crucial role in variability of NLC and of PMC on short- and long-term scales. Thus, turbulence, gravity and planetary waves, solar thermal and lunar gravitational tides produce significant variabilities of all basic atmospheric parameters, hence changing temporal and spatial evolution of NLC/PMC (Witt, 1962; Rapp et al., 2002; Kirkwood and Stebel, 2003; Chandran et al., 2010; Dalin et al., 2010, 2011; Pautet et al., 2011; Taylor et al., 2011; Fiedler et al., 2011; Pertsev et al., 2015; von Savigny et al., 2017). In particular, daily

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https://doi.org/10.1016/j.jastp.2018.01.025
Received 2 November 2017; Received in revised form 15 December 2017; Accepted 23 January 2018

Please cite this article in press as: Dalin, P., et al., Response of noctilucent cloud brightness to daily solar variations, Journal of Atmospheric and Solar-Terrestrial Physics (2017), https://doi.org/10.1016/j.jastp.2018.01.025

and day-to-day temperature variations are about 6–15 K due to gravity waves (Rapp et al., 2002; Rauthe et al., 2006; Offermann et al., 2009), about 2–10 K due to traveling planetary waves (Merkel et al., 2008; Offermann et al., 2009; Dalin et al., 2011; Stevens et al., 2017), and 0.5–6 K due to solar thermal tides (Forbes, 1982a,b; Offermann et al., 2009; Fiedler et al., 2011; Stevens et al., 2017).

Besides natural atmospheric dynamics, variability of solar ultraviolet irradiance produces pronounced effects on the upper mesosphere radiative-photochemical state and to a lesser extent on the NLC/PMC radiative-photochemical-thermodynamic state (e.g., Brasseur and Solomon, 1984; Thomas et al., 2015). The solar Lyman-α flux at 121.6 nm is the primary component in the solar spectrum that drives atmospheric changes at altitudes of 70–100 km and exhibits large variability (by factor of 2) in the course of the well-known 11-year solar activity cycle (Woods and Rottman, 1997; Beig et al., 2008). Model studies (Schmidt et al., 2006; Marsh et al., 2007) as well as ground-based OH measurements (e.g., Ammosov et al., 2014; Kalicinsky et al., 2016; Perminov et al., 2017) demonstrate a positive temperature response of several degrees (1–10 K) in the mesopause region when solar activity changes from its minimum to maximum. A similar temperature (T) response of 4–5 K at 80 km altitude to solar activity was found by Hervig and Siskind (2006) using UARS HALOE satellite data. Changes in the water vapor (H_2O) concentration in the summer mesopause and above anticorrelate with solar activity mainly by Lyman-α flux-induced photodissociation of water molecules (e.g., Brasseur and Solomon, 1984; Lübken et al., 2009; Hartogh et al., 2010). Changes in T and H_2O translate into a moderate influence of the 11-year solar activity on the quasi-decadal variability in NLC/PMC characteristics. Thus, long-term ground-based NLC observations demonstrate that a significant part (20–60%) of the overall variance in the NLC occurrence frequency and brightness can be explained due to the 11-year solar variability (Dalin et al., 2006; Kirkwood et al., 2008; Dubietis et al., 2010; Pertsev et al., 2014). Satellite observations demonstrate a similar influence (30–65%) of solar activity on the total variance of the PMC extinction and albedo (brightness) in the Northern Hemisphere, depending on latitude bands and time intervals analyzed (Hervig and Siskind, 2006; DeLand et al., 2007; DeLand and Thomas, 2015).

Besides the long-term solar variability the short-term periodic perturbations in solar UV radiation occurring on a scale of 27 days (the Carrington solar rotation cycle) influence the middle atmospheric radiative-photochemical and dynamical state (Ebel et al., 1986; Hood et al., 1991; Beig et al., 2008). Tejfel (1957) was probably the first who proposed an idea that short-periodic changes in UV solar radiation can influence NLC brightness. Robert et al. (2010) were the first to demonstrate a 27-day solar signature in the NLC occurrence frequency by analyzing satellite data. Thurairajah et al. (2017) have analyzed PMC data and have found anticorrelation between variations in solar Lyman-α flux and variations in PMC ice water content, albedo and occurrence frequency. von Savigny et al. (2013) have analyzed NLC satellite observations and have found that NLC occurrence rate and albedo anomalies anticorrelate with Lyman-α flux anomalies in terms of the 27-day and the 11-year solar cycle.

In the present paper, we investigate a day-to-day response of the NLC brightness to day-to-day solar variations in the Lyman-α flux within the 27-day solar rotation cycle. Such an analysis is performed for the first time since it is based on ground-based NLC observations, carried out from different sites around the globe and for various time intervals and epochs.

2. Data source

We have analyzed daily ground-based NLC observations performed at the following sites of the Northern Hemisphere and for the following time periods:

- Scotland for 2006–2016,
- Canada for 1967–1977,
- Novosibirsk for 2004–2016,
- Moscow for 1962–2016,
- Lithuania for 1992–2016,
- Denmark for 2007–2016.

The observations have been conducted in summer time from about 20 May to 15 August. Since 2004, visual observations have been systematically supported by time-lapse digital photographic measurements in Novosibirsk and Moscow and later at other sites. The digital measurements provide continuous observations during a whole night and whole summer season with higher temporal resolution and precision compared to the visual observations. That is why the number of detected NLC displays has increased since the start of the “digital” era. At the same time, we apply the same procedure for assessment of NLC parameters both for the “digital” and “visual” observational era. In particular, the NLC brightness is visually estimated by the same procedure as described below. The total NLC number as well as the number of visual and digital NLC observations for each database is shown in Table 1. Since the Canadian NLC database contains observations made at different sites at different latitudes, we have selected only those sites which are located between 50° and 60°N in order to be consistent with NLC observations being made at midlatitudes of other databases. Details of the world-wide automated digital camera NLC network and observational techniques can be found in (Dalin et al., 2008; Dubietis et al., 2010, 2011; Zalcik et al., 2016).

As a proxy of the solar activity, daily solar Lyman-α flux data from 1962 to 2016 have been analyzed by means of satellite data obtained from the LASP Interactive Solar Irradiance Datacenter (LISIRD) and

Table 1

Sensitivity (S), along with its error (either 1.5 or 2 or 3 standard deviations), of the natural logarithm of the NLC brightness (B) to solar anomaly for various NLC databases for various time periods. The probability level of the respective S-value is shown in brackets. In the second column, the S–values are shown at time lag equal to zero day. In the third column, the maximum S-values are shown at respective average non–zero time lag (see the text). The exception is for the Moscow and Danish NLC databases, for which the maximum S-values are found at zero time lag. Statistically significant S-values (S is equal to or greater than its error) are marked in bold. The fourth column represents the coefficient of elasticity (E), i.e., the relative S-value in %/%. The fifth column yields the average lag and its statistical error range (in brackets) for the six databases (see text). The sixth column gives the number of positive (lag+), including zero, and negative (lag–) time lags determined for individual summer seasons for each database. The seventh column shows the number of visual (vis), digital (dig) as well as the total number (tot) of NLC observations for each database.

Site and time period	S [ln(B)/1 0^{11} ph cm^{-2} s^{-1}] @ lag = 0 day	S [ln(B)/1 0^{11} ph cm^{-2} s^{-1}] @ non–zero lag [day]	E (%/%)	lag and its error [days]	lag+/ lag–	vis/dig/tot
Scotland 2006–2016	**−0.27** ± **0.25** (90%)	**−0.28** ± **0.25** (90%); lag = 1	−0.04	1 (−6 +7)	7/4	0/304/304
Canada 1967–1977	**−0.19** ± **0.19** (90%)	**−0.23** ± **0.23** (95%); lag = 3	−0.02	3 (−4 +6)	9/2	969/0/969
Novosibirsk 2004–2016	**−0.32** ± **0.32** (95%)	**−0.34** ± **0.33** (95%); lag = 1	−0.05	1 (−7 +5)	9/4	0/249/249
Lithuania 1992–2016	**−0.20** ± **0.19** (90%)	**−0.29** ± **0.23** (95%); lag = 2	−0.05	2 (−1 +8)	11/14	275/258/ 533
Denmark 2007–2016	**−0.26** ± **0.25** (90%)		−0.04	0 (−6 +7)	4/6	0/197/197
Moscow 1962–2016	**−0.28** ± **0.28** (99%)		−0.05	0 (−4 +4)	31/20	465/350/ 815