Ground based observations of noctilucent cloud brightness and frequency

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Abstract

Since their first recorded appearance in 1885, noctilucent clouds (NLCs) have become more frequent in the twilight sky along with their satellite observed counterparts, polar mesospheric clouds (PMCs). Numerous studies have linked this phenomenon with increasing levels of methane and water vapour in the mesosphere, suggesting that this surge is a consequence of climate change. In this paper, we analyze ground based observations of NLCs from independent observers, aggregated by the Noctilucent Cloud Observing Network (NLCNET, 2020), and show that there has been an increase in NLC brightness and frequency over the 2014–2020 time period between the 50 °N to 60 °N latitudes. This trend is consistent with data on PMCs from the Aeronomy of Ice in the Mesosphere (AIM) satellite mission. There is also a correlation between minimum NLC frequency and the solar cycle maximum, with a time lag of around two years in the manner of Gadsden (1998).

1 Introduction

Noctilucent or *night-shining* clouds (NLCs) are a stunning phenomenon in the twilight sky. Formed by ice crystals in the mesosphere, they appear as shimmering, delicate waves in the darkening sky, close to the horizon just after sunset. They come in varying degrees of brightness, although they are generally very faint, and can be broadly classified by form into veils, bands, waves and whirls. In order to observe NLCs from the ground, just the right viewing conditions are required. They appear seasonally, typically in the summer at the higher latitudes when the mesosphere is coldest. For instance, NLCs are generally observed in the northern hemisphere between May and August. NLCs form at the highest altitude of all clouds, around 82 km. The fact that they are illuminated by scattered sunlight means that they are visible when the sun is between 6° to 16° below the horizon – too far below means that the band of formation is no longer sunlit, and too soon means that the sky is not dark enough for the clouds to stand out (Fogle and Haurwitz, 1966).

With time, the frequency of NLC observations has increased. For example, Russell III et al. (2014) observed an increase in the number of ground based NLC sightings over the years 2002-2011. Furthermore, this phenomenon is expanding to lower latitudes than seen before, occasionally even as low as 40 °N. Other studies (DeLand et al., 2003; DeLand and Thomas, 2015; Hervig et al., 2016) similarly observe increasing frequencies of polar mesospheric clouds (PMCs), which are the same phenomenon observed by satellites. The Noctilucent Cloud Observing Network (NLCNET, 2020) is an internet forum which compiles reports from NLC observers around the globe. This paper aims to characterize trends in these data, see if they are consistent with the aforementioned observations, and explore whether they can be used as a reliable source of information regarding NLC brightness and frequency in future studies.

The first recorded sightings of NLCs are as recent as 1885 (Schröder, 1999), which is surprising given that the sky has been an active area of interest and observation long before that. Thus, Thomas and Olivero (2001) have argued that this year marked a very abrupt increase in the occurrence of NLCs, if there were any at all before that. It has been hypothesised that the Krakatoa eruption in 1883 triggered NLC formation by injecting large amounts of water vapour and dust, which acts as condensation nuclei, into the atmosphere. The condensation nuclei of NLCs also largely consists of extraterrestrial material: meteor dust, which forms a layer enclosing the NLC level (Fogle and Haurwitz, 1966). Even exhaust from rockets have been known to cause NLC formation (Stevens et al., 2012).

The variation of NLC brightness and frequency depends on many factors such as mesospheric temperature, moisture levels and the solar cycle. Lower temperatures, together with high moisture levels favour the formation of ice crystals in the mesosphere. Sources of mesospheric moisture include volcanism, tropospheric water vapour carried upwards by Hadley cells, and methane oxidation. There is also an anticorrelation between solar flux at the Lyman-α wavelength and NLC activity (Gadsden, 1998). This is because solar ultraviolet radiation reduces the available moisture by breaking water molecules apart (photodissociation), and also raises the temperature of the mesosphere. NLC activity has been found to peak a year or two after a solar minimum and vice versa; the cause of this time lag is not clearly known today.

The role of methane in particular has been the center of many studies (Lübken et al., 2018; Thomas et al., 1989). The hypothesis that rising methane levels leads to increasing atmospheric water vapour, hence increased NLC activity, is a promising one. On the other hand, the observed NLC activity seems to be less pronounced than expected, so this cannot be the sole driving factor. Another explanation involves rising CO_2 levels, which reduces the temperature of the upper atmosphere thereby favouring NLC formation (DeLand et al., 2003; Goessling and Bathiany, 2016). These theories provide a direct link between NLCs and the greenhouse gas effect; if validated, the recent increase in NLC activity should be interpreted as warning bells for climate change.

In principle, the best way of charting global trends in NLCs is via satellite observations of mesospheric clouds. The Aeronomy of Ice in the Mesosphere (AIM) satellite mission (Russell III, 2020), launched in 2007, is dedicated to studying PMCs. Three important instruments onboard are the Solar Occultation For Ice Experiment (SOFIE), the Cloud Imaging and Particle Size (CIPS) experiment and the Cosmic Dust Experiment (CDE). Data from CIPS has been used to chart NLC frequencies between 2014 and 2020 in Fig. 1. As noted on the AIM Mission status page, the 2020 season is unprecedentedly early (the second earliest in their record extending back to 2007). The NLC frequencies for 2020 have also exceeded those in previous years at all stages.

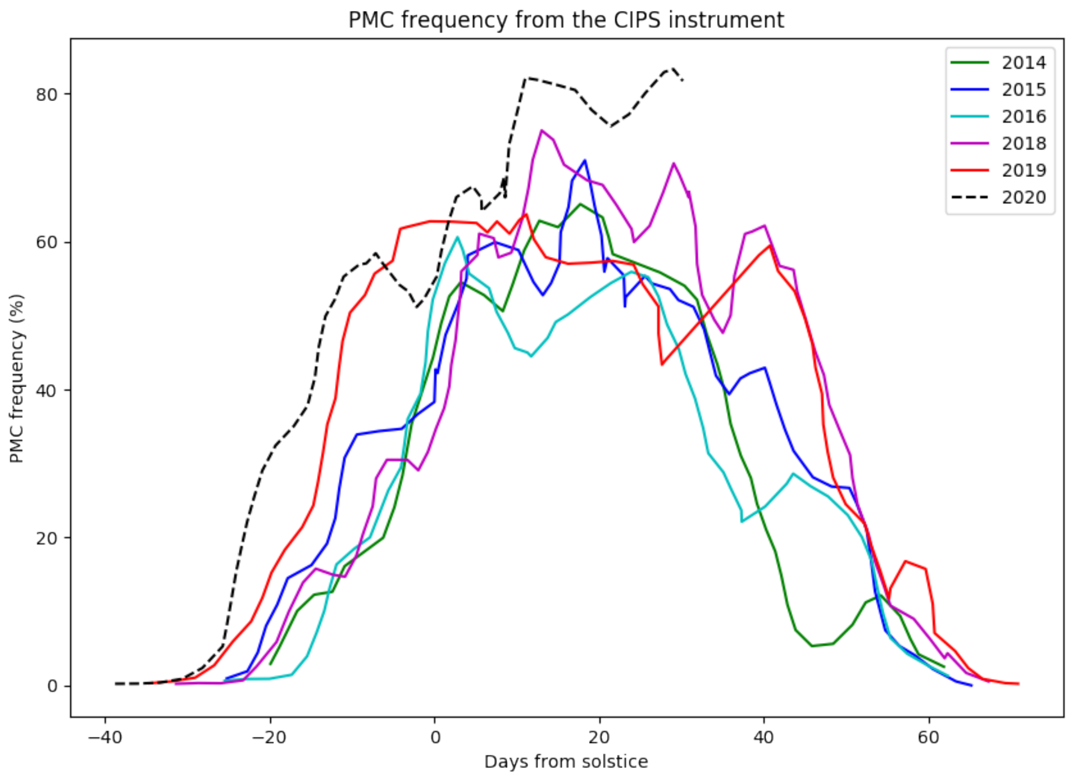


Figure 1: PMC frequency data at the 80° N latitude from the Cloud Imaging and Particle Size (CIPS) instrument. The most recent data is from 21 July, 2020.

2 Methods

2.1 Data collection

Data on PMCs, recorded by the CIPS instrument in the northern hemisphere between 2014 and 2020, has been obtained from the AIM satellite mission page (Russell III, 2020). PMC frequencies colour coded by year have been presented in Fig. 1.

Records of ground based NLC sightings, as well as negative reports, have been gathered from the Noctilucent Cloud Observing Network (NLCNET, 2020). We have used a total of 2148 positive reports, with 560 negative reports. Only records from 2014 to 2020 have been considered, due to the unavailability of negative reports from before that period. Each record consists of the name of the observer, the location and date of the sighting, and the approximate brightness of the NLC on a scale of 1 to 5. All observations are from locations in the Northern hemisphere, hence the times range from between May and August each year, concentrated around the summer solstice (21 June). Specifically, the majority of records are from the 50 °N to 60 °N latitude range. The variation of the number of positive reports over a season (between May and August), colour coded by year, has been presented in Fig. 2.

The solar cycle variations have been inferred from the Lyman-alpha Model Solar Spectral Irradiance Time Series, provided by the Laboratory for Atmospheric and Space Physics (LASP, 2020), accessed from the LASP Interactive Solar Irradiance Data Center (LISIRD) webpage.

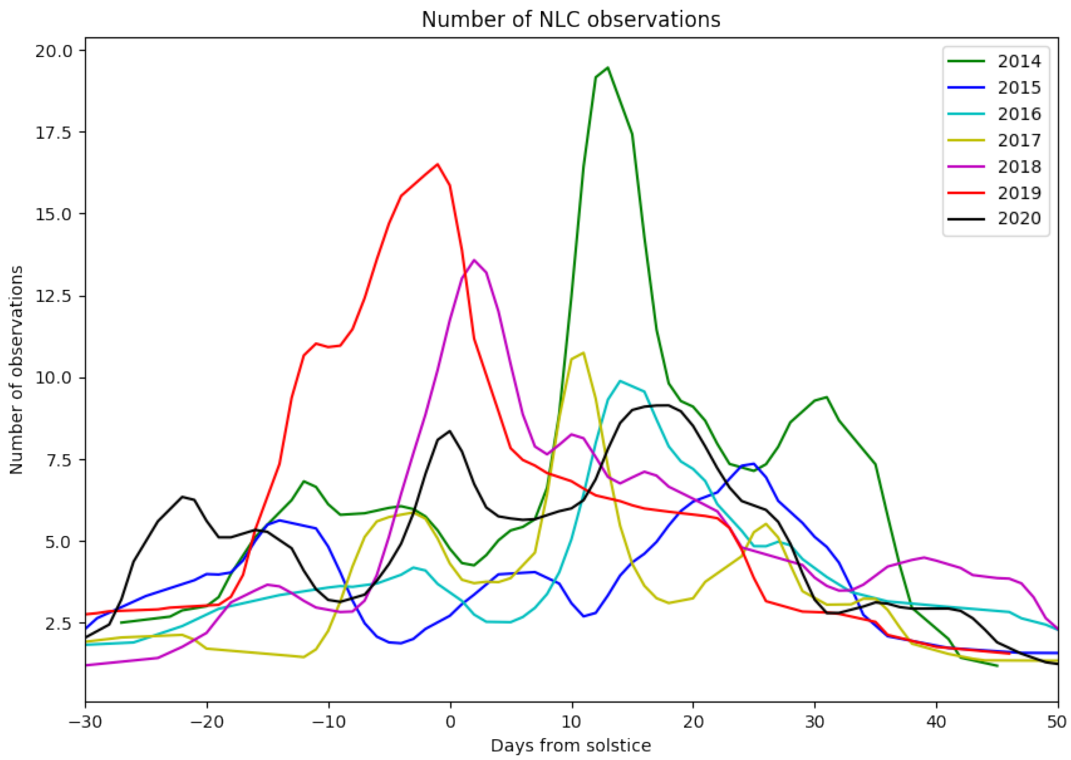


Figure 2: Number of observations per day, coloured by year. The raw data has been smoothed by a Gaussian filter ($\sigma = 2$).

2.2 Indices of brightness and frequency

In order to evaluate the variation of observed NLC brightness over time, we develop a brightness index. If there are n_d reports of NLC's on a single day, each with brightness b_i, along with n_d^- negative reports, we develop the daily brightness index

$$\beta_d = \frac{1}{n_d + n_d^-} \sum_{i=1}^{n_d} b_i.$$

This is simply the mean brightness $\sum b_i/N$ for $N = n + n^-$, if we interpret negative reports as having brightness $b_i = 0$. Similarly, given n_m reports in a month of brightness b_i each, along with n_m^- negative reports, we develop the monthly brightness index

$$\beta_m = \frac{1}{n_m + n_m^-} \sum_{i=1}^{n_m} b_i.$$

We develop analogous measures of the frequencies of positive NLC reports, daily (f_d) and and monthly (f_m).

$$f_d = \frac{n_d}{n_d + n_d^-}, \qquad f_m = \frac{n_m}{n_d + n_m^-}.$$

2.3 Statistical analysis

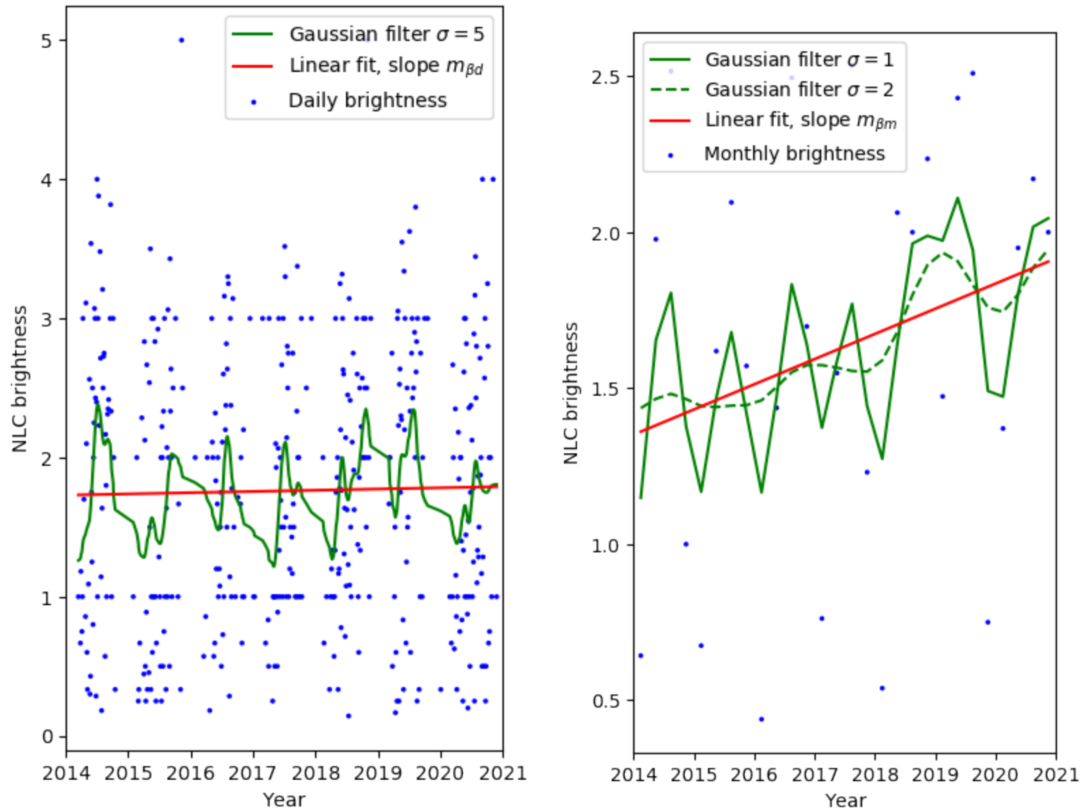
All data was processed using the `pandas` python library, and all calculations were run using python scripts. The `scipy.ndimage` package was used for smoothing the data via a

Gaussian filter. The `scipy.stats` package was used for linear regression, and `matplotlib` was used to generate all plots. A p-value less than or equal to 0.05 is considered as the cutoff for statistical significance.

3 Results

3.1 Mean brightness of NLCs

The progression of β_d and β_m has been presented in Fig. 3, along with the slopes m_β of the linear regression.



(a) β_d ($m_{\beta d} = 0.009 \pm 0.006$) (b) β_m ($m_{\beta m} = 0.08 \pm 0.02$)

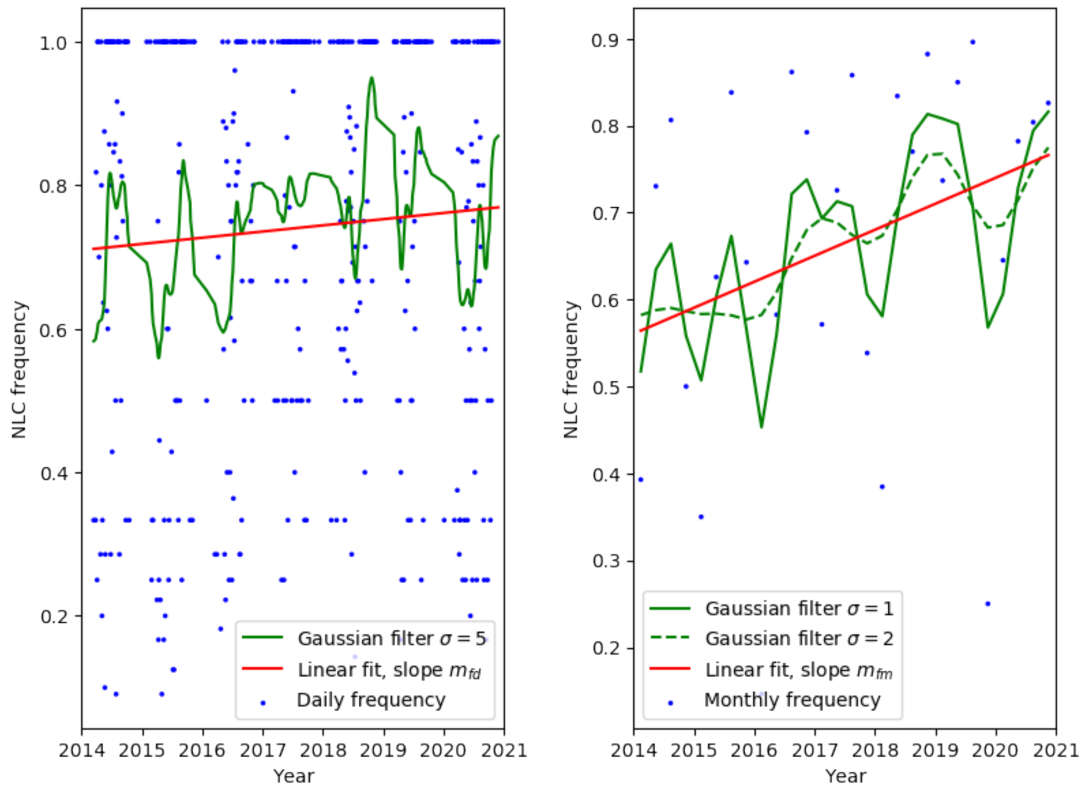
Figure 3: Brightness indices evaluated (a) for each day (b) over each month. Note that each interval of one year contains only the four months May through August.

While the daily brightness index β_d shows no global trend, the mean monthly brightness β_m in Fig. 3 does show a statistically significant increase over the past seven years.

The difference between daily and monthly trends can be ascribed to the irregularity of reports, especially negative reports over a single day. When averaged over a month, these trends become more stable. We have considered a fairly short time interval, so the actual progression of brightness over longer intervals is unlikely to be remain linear.

3.2 Frequencies of NLCs

The progression of NLC frequencies have been presented in Fig. 4, along with the slopes m_f of the linear regression.



(a) f_d ($m_{fd} = 0.009 \pm 0.002$) (b) f_m ($m_{fm} = 0.03 \pm 0.01$)

Figure 4: NLC frequencies evaluated (a) for each day (b) over each month.

Similar to brightness data, the monthly trends are much steeper than daily ones. Both show a statistically significant increase in frequency of NLCs.

4 Discussion and Conclusions

NLCNET data has shown that NLCs have indeed become brighter and more frequent since 2014, which is consistent with CIPS readings. This indicates that the mesophere has become cooler and more moist over time. One common feature between data from CIPS (Fig. 1) and NLCNET (Fig. 2) are the early NLC seasons of 2019 and 2020, which are reminiscent of a similar early season in 2007 (Dalin et al., 2011). This timespan suggests an influence of the 11 year solar cycle, which certainly affects temperatures in the mesosphere (Beig et al., 2008), thereby affecting NLC activity. Over our time period of consideration, solar Lyman-α flux has fallen from its peak in 2014 (LASP, 2020). Both CIPS and NLCNET data (Fig. 4) suggest that NLC frequencies reached a minimum around 2016, which agrees with Gadsden (1998) where he observes that a minimum in NLCs occurs two years after a solar maximum. Therefore, NLCNET data is consistent with CIPS, and the role of solar flux is evident. NLCNET data over multiple solar cycles need to be considered to quantitatively account for the solar forcing factor.

As Pertsev et al. (2014) have observed, there is a discrepancy in the literature between long term trends in PMC frequency, which suggest a positive trend, and ground based NLC frequency, which has so far shown a zero trend. It must be noted that the NLCNET dataset is inhomogeneous, in the sense that it draws from multiple observation stations at different latitudes. Russell III et al. (2014) have shown that trends in PMCs at higher latitudes are expected to be flatter than elsewhere, as cloud frequencies there are already very high, close to 100%. Furthermore, the role of the solar cycle is almost absent at these higher latitudes, while it is significant at lower ones. Now, the majority of reports from NLCNET are from Europe, countries in the 50 °N to 60 °N latitude range, so the increased frequency of NLCs which we have observed fits well with Russell III et al. (2014). We use this argument to explain why the trends in the CIPS data, which are taken at 80 °N, are not as prominent.

We conclude that NLCNET data is consistent with previous findings in the field and is thus a valuable resource for amateur observers and researchers alike, more so as the database grows over time. While our analysis does suggest that NLCs have become brighter and more frequent over the past few years, some key problems noted by Zahn (2003) remain, namely the extreme variability in data. Ground based observations further complicate this as local weather conditions can greatly affect NLC detection. It is also difficult to isolate a single factor responsible for our observed trends, be it solar forcing, methane, CO_2, or some yet unknown influence. Thus, our analysis can be improved by making additional corrections for visibility, latitude and solar flux. Nevertheless, it is evident that increased NLC activity, especially in the mid latitudes where they are becoming more noticeable over time, is a very tangible, easily observed effect of climate change. This is indicative of lowering temperature and increasing water vapour in the mesosphere, perhaps over the course of a century. If increasing methane and CO_2 are indeed the driving force behind this change, NLCs represent a very direct consequence of greenhouse gas emissions. While the clouds themselves may not have any significant impact on climate, they serve as a reminder of how human activity can shape our planet in unexpected ways.

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