Journal of Atmospheric and Solar-Terrestrial Physics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

First identification of lunar tides in satellite observations of noctilucent clouds

Christian von Savigny [a,*], Matthew T. DeLand [b], Michael J. Schwartz [c]

[a] Institute of Physics, Ernst-Moritz-Arndt-University of Greifswald, Felix-Hausdorff-Str. 6, Greifswald 17487, Germany
[b] Science Systems and Applications Inc., 10210 Greenbelt Rd., Lanham, Maryland, MD 20706, USA
[c] Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

ARTICLE INFO

Article history:
Received 15 March 2016
Received in revised form
2 June 2016
Accepted 1 July 2016

Keywords:
Noctilucent clouds
Polar mesospheric clouds
Lunar tides

ABSTRACT

Noctilucent clouds (NLCs) are optically thin ice clouds occurring near the polar summer mesopause. NLCs are a highly variable phenomenon subject to different sources of variability. Here we report on a poorly understood mechanism affecting NLCs, i.e., the lunar gravitational tide. We extract remarkably clear and statistically highly significant lunar semidiurnal tidal signatures in NLC occurrence frequency, NLC albedo and NLC ice water content from observations with the Solar Backscatter Ultraviolet (SBUV) satellite instruments using the superposed epoch analysis method applied to a data set covering more than 3 decades. The lunar semidiurnal tide is identified in NLC measurements in both hemispheres. In addition, lunar semidiurnal tidal signatures in polar summer mesopause temperature were extracted from space borne observations with the Microwave Limb Sounder (MLS) and the phases of the lunar tidal signatures in NLC parameters and temperature are demonstrated to be consistent. To our best knowledge these results constitute the first identification of the lunar tide in non-visual NLC observations.

1. Introduction

The moon is responsible for gravitational tidal signatures in the Earth's atmosphere and the semidiurnal lunar tide with a period of 12.421 h is the most important of these signatures (Chapman and Lindzen, 1970). This lunar tidal signature has been identified in surface pressure for the first time in 1842 (Sabine, 1847), but the effect of the lunar tidal forcing on the Earth's atmosphere in general is not fully understood. Lunar semidiurnal tidal signatures have been reported in several parameters in the Earth's Mesosphere/Lower Thermosphere (MLT) region, including winds (e.g., Stening et al., 2003), temperature (e.g., Forbes et al., 2013; Paulino et al., 2013) and airglow emissions (e.g., von Savigny et al., 2015). In terms of NLCs, lunar tidal signatures have been reported in a very limited number of earlier studies based on visual cloud observations (i.e., Kropotkina and Shefov, 1975; Gadsden, 1985; Gadsden and Schroeder, 1989; Dalin et al., 2006). However, these results are partly contradictory and have not yet been confirmed with more objective instrumentation (see also Section 4.3).

NLCs have become a focus of middle atmospheric research because of their potential role as sensitive indicators of middle atmospheric climate change (e.g., Thomas et al., 1989; von Zahn, 2003). They are a highly variable phenomenon subject to different sources of variability including gravity (e.g., Witt, 1962) and planetary waves (e.g., von Savigny et al., 2007), solar variability (e.g., Thomas et al., 1991; Robert et al., 2010), interhemispheric (e.g., Becker and Fritts, 2006) as well as intra-hemispheric coupling (e.g., Gumbel and Karlsson, 2011). An essential aspect of current NLC research is to improve the scientific understanding of the sources of variability in NLCs and the polar summer mesopause region at temporal scales from days to decades. The only instrumental NLC data set that covers multiple decades is based on Nadir UV observations with the Solar Backscatter Ultraviolet (SBUV) instruments on a series of different satellites, providing continuous NLC observations since 1979 (DeLand et al., 2007; DeLand and Thomas, 2015). The most recent version (V4) of the SBUV(/2) NLC data product includes retrievals of NLC ice water content (IWC), in addition to the NLC residual albedo, i.e., the ratio of the backscattered and Rayleigh corrected radiance and solar irradiance (DeLand and Thomas, 2015). Moreover, cloud occurrence rates can be derived from the data product. In this study, we search for lunar tidal signatures in all three NLC parameters, applying the superposed epoch analysis method to the SBUV(/2) NLC data set during the northern and southern hemisphere NLC seasons from 1979 to 2011. The main motivation for this study was to investigate, whether lunar tidal signatures can be identified in non-visual NLC observations.

* Corresponding author.
E-mail address: csavigny@physik.uni-greifswald.de (C.v. Savigny).

http://dx.doi.org/10.1016/j.jastp.2016.07.002
1364-6826/

2. NLC retrievals from SBUV measurements

The Solar Backscatter UltraViolet (SBUV) instrument was originally built to provide measurements of stratospheric ozone. Continuous observations started in 1978 with an SBUV instrument on Nimbus-7. Modified versions of the instrument (SBUV/2) were flown on the NOAA-9, NOAA-11, NOAA-14, NOAA-16, NOAA-17 and NOAA-18 spacecraft, and the SBUV(/2) observations currently cover more than 3 and a half decades. The SBUV(/2) instruments perform measurements of backscattered solar radiation at 12 wavelengths between 252 nm and 340 nm. NLCs can be detected in the SBUV(/2) nadir observations, because they lead to small enhancements in backscattered radiance above the Rayleigh scattered background (Thomas et al., 1991). The SBUV(/2) NLC data has been extensively used for NLC studies in the past (e.g., DeLand et al., 2007; Shettle et al., 2009; Robert et al., 2010; DeLand and Thomas, 2015). For this study, the latest version (V4) of the SBUV (/2) NLC data product has been used, which also includes NLC ice water content. Cloud ice water content is retrieved from the cloud residual albedo at a wavelength of 273 nm as described in DeLand and Thomas (2015). Note that only measurements with the highest quality flag (31) are used in this study.

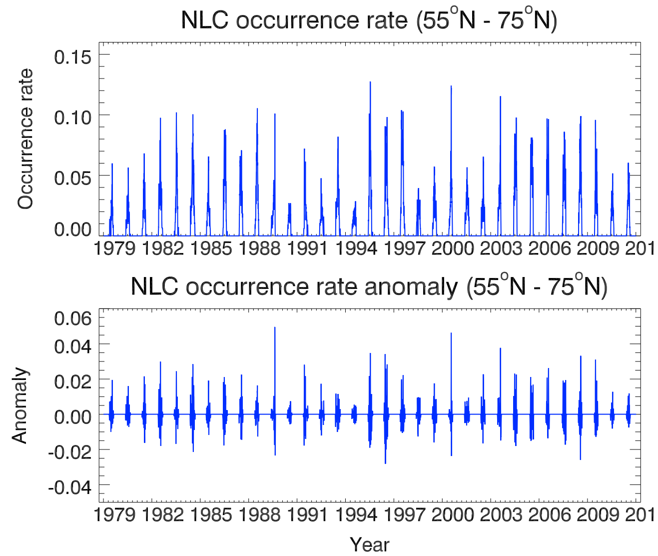

Fig. 1. Top panel: NLC occurrence rate time series for all northern hemisphere NLC seasons from 1979 to 2011 and the 55°N to 75°N latitude range. Bottom panel: NLC occurrence rate anomaly determined by removing a 20-day running mean from the time series in the top panel.

3. Data analysis

Table 1 provides an overview of the SBUV(/2) data sets used in this study. The SBUV(/2) NLC data sets (including NLC occurrence rate, albedo and ice water content) were analyzed using the superposed epoch analysis method (Chree, 1912). A similar approach was recently successfully applied by von Savigny et al. (2015) to extract lunar semidiurnal tidal signatures in terrestrial airglow emissions. The data sets were first daily and zonally averaged and binned into the 55° to 75° latitude bin – in both hemispheres. A wide latitude bin is in principle desirable, because a larger number of individual measurements should lead to more significant results. However, the highest latitudes covered by the SBUV(/2) instruments are characterized by a rapid variation of measurement local solar time (LST) with latitude and are, therefore, avoided here. The local solar times of the SBUV(/2) measurements used in this study are also listed in Table 1. The range of local solar times given for individual satellites is mainly caused by the slow local solar time drift of the satellite orbits (see, e.g., Fig. 2 in DeLand et al., 2007). Note that for the 55° to 75°N latitude band the SBUV (/2) instruments detect about 200–1000 NLCs per season (typically less in the SH), i.e., the total number of identified NLCs is significantly larger than for the lunar tidal studies based on ground-based visual NLC observations (Kropotkina and Shefov, 1975; Gadsden and Schroeder, 1989; Dalin et al., 2006).

A few gaps in temporal coverage exist in the SBUV(/2) data base. The missing days were linearly interpolated in time. The zonally and daily averaged NLC time series were then smoothed with a 5-day running mean – similar as in von Savigny et al. (2015) – in order to reduce the inherent variability in the SBUV(/2) NLC data sets. The top panel of Fig. 1 shows as an example the NLC occurrence rate time series for the 55°N to 75°N latitude range. An 11-year solar cycle signature – discussed more quantitatively by DeLand et al. (2003) – is evident. In the next step, anomaly time series are determined by removing a 20-day running mean from each time series. Choosing a 20-day window is arbitrary to a certain extent, but tests with different smoothing window widths essentially lead to the same results, consistent with previous studies (Robert et al., 2010; von Savigny et al., 2015). The bottom panel of Fig. 1 shows the anomaly time series obtained from the time series displayed in the top panel of the figure.

For each day, the lunar time (τ) of the observations is determined from the known local solar time (t) of the observations and the lunar phase angle (ν) according to $\tau = t - \nu$ as in Forbes et al. (2013). Then the anomalies are sorted according to lunar time (from 0 to 12 lunar hours), and all anomaly values within a 1-h lunar time bin are averaged. The basic idea behind this approach is that all other sources of variability, which are uncorrelated to lunar time cancel out, while the lunar semidiurnal tidal signature remains.

Table 1
Overview of satellite data sets used for the lunar tidal analysis in both hemispheres.

Northern hemisphere			Southern hemisphere		
Period	Satellite	Local solar time	Period	Satellite	Local solar time
1979–1984	Nimbus-7	9–11	1979/1980–1984/1985	Nimbus-7	13–14
1985–1989	NOAA-09	12–16	1985/1986–1989/1990	NOAA-09	16–20
1990–1994	NOAA-11	12–16	1990/1991– 1994/1995	NOAA-11	15–20
1995–2000	NOAA-14	12–15	1995/1996–2000/2001	NOAA-14	15–19
2001–2002	NOAA-16	12–13	2001/2002–2007/2008	NOAA-16	15–17
2003–2011	NOAA-17	18–21	2010/2011–2011/2012	NOAA-16	16–19

4. Results and discussion

4.1. Semidiurnal lunar tide in NLC parameters

We first present the results for the northern hemisphere, followed by the southern hemisphere results. Fig. 2 shows relative lunar semidiurnal tidal signatures in NLC occurrence rate (panel a), NLC albedo (panel b), and NLC ice water content (panel c) for the 55°N to 75°N latitude range, extracted using the superposed epoch method described above. The relative lunar tidal signatures were determined by dividing the absolute signatures by the mean values of all NLC seasons studied. The black lines and solid circles correspond to the epoch averaged anomalies. The error bars represent the standard errors of the mean based on all individual anomaly values in a given 1-h lunar time bin. Note that these error bars reflect both natural variability and measurement errors.