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Mid-latitude mesospheric clouds and their environment from SOFIE observations

Mark E. Hervig [a,*], Michael Gerding [b], Michael H. Stevens [c], Robert Stockwell [d], Scott M. Bailey [e], James M. Russell III [f], Gunter Stober [b]

[a] GATS, Inc., Driggs, Idaho 83422, USA
[b] Leibniz-Institute of Atmospheric Physics, University Rostock, Kühlungsborn, Germany
[c] Space Science Division, Naval Research Laboratory, Washington, DC, USA
[d] GATS, Inc., Boulder, Colorado 80301, USA
[e] Virginia Polytechnic Institute, Blacksburg, Virginia, USA
[f] Hampton University, Hampton, Virginia, USA

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A B S T R A C T

Observations from the Solar Occultation For Ice Experiment (SOFIE) on the Aeronomy of Ice in the Mesosphere (AIM) satellite are used to examine noctilucent clouds (NLC) and their environment at middle latitudes (~56°N and ~52°S). Because SOFIE is uniquely capable of measuring NLC, water vapor, and temperature simultaneously, the local cloud environment can be specified to examine what controls their formation at mid-latitudes. Compared to higher latitudes, mid-latitude NLCs are less frequent and have lower ice mass density, by roughly a factor of five. Compared to higher latitudes at NLC heights, mid-latitude water vapor is only ~12% lower while temperatures are more than 10 K higher. As a result the reduced NLC mass and frequency at mid-latitudes can be attributed primarily to temperature. Middle and high latitude NLCs contain a similar amount of meteoric smoke, which was not anticipated because smoke abundance increases towards the equator in summer. SOFIE indicates that mid-latitude NLCs may or may not be associated with supersaturation with respect to ice. It is speculated that this situation is due in part to SOFIE uncertainties related to the limb measurement geometry combined with the non-uniform nature of NLCs. SOFIE is compared with concurrent NLC, temperature, and wind observations from Kühlungsborn, Germany (54°N) during the 2015 summer. The results indicate good agreement in temperature and NLC occurrence frequency, backscatter, and height. SOFIE indicates that NLCs were less frequent over Europe during 2015 compared to other longitudes, in contrast to previous years at higher latitudes that showed no clear longitude dependence. Comparisons of SOFIE and the Solar Backscatter Ultraviolet (SBUV) indicate good agreement in average ice water column (IWC), although differences in occurrence frequency were often large.

1. Introduction

Noctilucent clouds (NLC) consist of ice particles that contain miniscule amounts of meteoric smoke and form near 83 km altitude during summer (Hervig et al., 2012). They are most often observed poleward of roughly 50° latitude, and scientists using satellite measurements have coined the phrase polar mesospheric cloud (PMC) to describe the ~83 km ice layer at high latitudes (e.g., Donahue et al., 1972; Thomas and Olivero, 1989). The distinction between NLC and PMC is semantic, where NLC typically refers to visual (naked eye) observations of the ~83 km ice layer, and generally connotes latitudes lower than roughly 66° where humans report sightings (e.g., Kirkwood et al., 2008). The upper latitude boundary is due to the lack of twilight conditions during summer, which are required for NLC to be seen by eye, while the lower boundary is roughly where temperatures are no longer low enough to support ice.

There have been conflicting reports concerning an apparent increase in mid-latitude NLC sightings and a possible spread of NLC to lower latitudes (e.g., Taylor et al., 2002; Dalin et al., 2006; Dubietis et al., 2010). For example, while visual observations reported by Kirkwood et al. (2008) indicate no trend in NLC at mid-latitudes from 1964–2006, satellite data reported by Russell et al. (2014) indicate a very small increase in mid-latitude NLCs that is consistent with cooling of the mesopause region during 10 years from 2002–2011. It should be noted that the visual NLC trends

* Corresponding author.
E-mail address: m.e.hervig@gats-inc.com (M.E. Hervig).

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reported in Kirkwood et al. (2008) were residual trends from multiple regression to three terms (linear trend, solar flux, and length of summer in the stratosphere). The residual trends were therefore reduced by the linear components of the solar and stratosphere vectors, and thus smaller than the total linear trend contained in the NLC data (Hervig and Stevens, 2014). In particular a steady decline in solar flux during the satellite era would reduce the residual trends (Lean and Rind, 2008), and it is suspected that the total NLC trends are slightly larger than the residual trends reported in Kirkwood et al. (2008). A recent investigation using Solar Backscatter Ultraviolet (SBUV) and Solar Occultation For Ice Experiment (SOFIE) measurements (Hervig et al., 2016) showed that NLC ice water column (IWC) increased, temperatures (T) decreased, and water vapor increased at NLC heights for high latitudes (67°–77° North or South) from 1979–2014. The results for Northern mid-latitudes (57°N), however, indicate that changes in IWC ($1.6 \pm 2.3\%$ decade^{-1}), T (-0.2 ± 0.3 K decade^{-1}), and H_2O (0.03 ± 0.04 K decade^{-1}) were less than half of the changes at 77°N, and furthermore not statistically different from zero. They also showed that the NLC record for Southern mid-latitudes (57°S) was sparse enough to prevent a reliable determination of trends, in both the satellite and model results.

SOFIE observations during 2007–2013 covered latitudes near 69° during summer in both hemispheres. Changes in the Aeronomy of Ice in the Mesosphere (AIM) orbit since 2013 have resulted in NLC observations at middle latitudes, in particular ~55°N during 2015 and ~52°S during 2014–15. Because SOFIE possesses excellent sensitivity and precision, the new observations provide a unique opportunity to characterize mid-latitude NLCs and their environment. SOFIE is compared to a variety of mid-latitude observations in Section 3. Mid-latitude SOFIE NLC measurements are compared to observations by the Solar Backscatter Ultraviolet (SBUV) and Solar Mesosphere Explorer (SME) satellite instruments. Temperature measurements are compared to coincident satellite profiles from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) experiment and from the Microwave Limb Sounding (MLS) experiment. SOFIE observations during the summer of 2015 often occurred near the Leibniz Institute of Atmospheric Physics (IAP), in Kühlungsborn, Germany (54.1°N, 11.8°E). The IAP uses ground-based lidar and radar systems to characterize, NLCs, temperature, and winds (e.g., Gerding et al., 2013a, 2013b), and these measurements are compared to coincident SOFIE observations in Section 4. Finally, SOFIE results are used to characterize differences between middle and high latitude NLCs and their environment in Section 5.

2. SOFIE

SOFIE was launched in April 2007 onboard the AIM satellite (Russell et al., 2009) to measure temperature, the abundance of five gaseous species (O_3, H_2O, CO_2, CH_4, and NO), NLCs, and meteoric smoke (Gordley et al., 2009; Hervig et al., 2009a; Marshall et al., 2010). SOFIE monitors the reduction in solar intensity as rays pass through the atmosphere on tangent paths during sunrise or sunset as viewed from orbit. The SOFIE field-of-view (FOV) subtends ~1.6 km vertically and the detectors are oversampled at ~0.2 km intervals. The limb measurements span a long atmospheric path length (~300 km) which results in inherent spatial averaging, but also contributes to high sensitivity when combined with the bright solar source and a very precise electro-optical system. SOFIE observes 15 sunsets (and 15 sunrises) each day, at the same latitude and local solar time (LT). Spacecraft sunrise (earth sunset) measurements occur in the Northern Hemisphere (NH) with sunsets in the Southern Hemisphere (SH).

SOFIE observations are used to identify NLCs and to determine a variety of ice layer properties. The most straightforward of these include the NLC top altitude (Z_{TOP}), the altitude of peak ice mass density (Z_{MAX}), and the bottom altitude of the ice layer (Z_{BOT}). Ice mass density (M_{ice}) is nearly a direct measurement, and the vertical integral of M_{ice} yields IWC. Multi-wavelength measurements furthermore yield the ice particle phase, shape, temperature, size, concentration, and meteoric smoke content (Hervig et al., 2009a, 2012; Hervig and Gordley, 2010). This study used SOFIE version 1.3 (V1.3) summary files, which contain all of the ice layer parameter retrievals (available online at sofie.gats-inc.com).

The SOFIE NLC identification criteria were revisited for the present study. Ice identification requires a number of criteria to be satisfied (for details see Hervig et al. (2009a)), including that the extinction is greater than the noise, the wavelength dependence of extinction is consistent with ice, and the ice layer is thicker than the SOFIE vertical FOV dimension (1.6 km). The latter criterion was found to cause a few thin NLC layers to be missed. The SOFIE measurement oversampling (0.2 km) is maintained through the retrieval process, which allows some flexibility in post analysis. Tests indicate that relaxing the vertical extent requirement to 1.0 km (5 data points) allows many thin NLC layers to be identified, without the inclusion of false detections. This change resulted in only a few more NLCs ($<5\%$ increase) in the NH seasons at high latitudes, and 12% more in the mid-latitude NH 2015 season (which is the focus of this study). The changes were larger in the SH, with 5–15% more NLCs for 2007–2013 (higher latitudes), and 50% more in the mid-latitude SH 2014–15 (52°S).

For observations of ice layers that are horizontally non-uniform, certain geometric errors could be present in the SOFIE retrievals. The error mechanisms are relevant because the mid-latitude NLC seasons had very low ice occurrence frequencies (-1% to 30%, see below), which implies a high degree of spatial inhomogeneity. One potential error is that an isolated cloud within the line-of-sight (LOS) but not at the tangent point will be assigned an erroneously low altitude. This is illustrated in Fig. 1a, where the NLC at 83 km, but displaced to one side of the tangent point, would erroneously be assigned a lower altitude in SOFIE measurements. Another potential error is that the retrieval of ice extinction (proportional to M_{ice}) assumes that ice is horizontally uniform within the FOV. If, however, ice occupies only a fraction of the FOV, then the retrieved extinction will be underestimated (see Hervig et al., 2009a for details). This occurs because the forward model will effectively spread the target over the geometric path length, with a reduced extinction level to accommodate the erroneously large path length. An additional factor is the reduction in actual path length (Fig. 1b) for off-tangent clouds, which can further cause an extinction underestimate when sampling patchy NLCs with SOFIE. Finally, Fig. 1a serves to illustrate another potential error where a NLC is offset from the tangent point, and thus does not correspond to the tangent point T and H_2O. The upcoming discussion will refer to the error mechanisms discussed here. Note that the errors discussed here for solar occultation could be present in other limb viewing cloud measurements including limb emission or limb scatter (e.g., SME). Note that for measurements of the gaseous atmosphere, that the errors discussed above are generally negligible, or inapplicable in the case of possible altitude biases.

3. Comparison of SOFIE and other satellites

3.1. SOFIE, SABER, and MLS temperatures

SOFIE temperatures were compared to coincident profiles from SABER (Remsberg et al., 2008) and from MLS (Waters et al., 2006). Comparing coincident profiles in the NH during June 2015