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Exploring noctilucent cloud variability using the nudged and extended version of the Canadian Middle Atmosphere Model

Maartje Kuilman*, Bodil Karlsson, Susanne Benze, Linda Megner

Stockholm University, Department of Meteorology, Stockholm University, 106 91 Stockholm, Sweden

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ABSTRACT

Ice particles in the summer mesosphere – such as those connected to noctilucent clouds and polar mesospheric summer echoes - have since their discovery contributed to the uncovering of atmospheric processes on various scales ranging from interactions on molecular levels to global scale circulation patterns. While there are numerous model studies on mesospheric ice microphysics and how the clouds relate to the background atmosphere, there are at this point few studies using comprehensive global climate models to investigate observed variability and climatology of noctilucent clouds. In this study it is explored to what extent the large-scale inter-annual characteristics of noctilucent clouds are captured in a 30-year run - extending from 1979 to 2009 - of the nudged and extended version of the Canadian Middle Atmosphere Model (CMAM30). To construct and investigate zonal mean inter-seasonal variability in noctilucent cloud occurrence frequency and ice mass density in both hemispheres, a simple cloud model is applied in which it is assumed that the ice content is solely controlled by the local temperature and water vapor volume mixing ratio. The model results are compared to satellite observations, each having an instrument-specific sensitivity when it comes to detecting noctilucent clouds. It is found that the model is able to capture the onset dates of the NLC seasons in both hemispheres as well as the hemispheric differences in NLCs, such as weaker NLCs in the SH than in the NH and differences in cloud height. We conclude that the observed cloud climatology and zonal mean variability are well captured by the model.

1. Introduction

In the summer night sky at high latitudes, one can sometimes see clouds that seem to emit light. In fact, this observable light is sunlight, scattered by very thin ice clouds, which are located as high as 80–85 km above the Earth's surface. These ice clouds are called noctilucent clouds (NLCs) or polar mesospheric clouds (PMCs) and were first documented in the 1880s (e.g., Leslie, 1885).

NLCs form only in the high latitude summer mesosphere, which is the coldest place in the earth-atmosphere system. The reason for the extremely low temperatures in this region is the residual circulation of the middle atmosphere (e.g. Andrews et al., 1987). This meridional flow of air – driven by the momentum from gravity wave breaking (Lindzen, 1981) – drives air upwards in the summer polar mesosphere. Because the air is cooled adiabatically when rising, this region is extremely cold. At the same time in the winter mesosphere, the air descends and heats adiabatically. The transition between mesospheric summer and winter flow occurs near the equinoxes, after which the summer-to-winter circulation slowly builds up to reach its peak strength close to the solstices.

In the northern hemisphere (NH), a typical NLC season lasts from late May until the end of August. In the southern hemisphere (SH), NLCs are present from late November until mid - February (e.g. Thomas and Olivero, 1989). Observations show that NLCs vary in both occurrence frequency and brightness on various time scales. In the SH, the variability is particularly high, both in the onset of the NLC season and in its mid-season occurrence frequency. In the NH, on the other hand, the NLC occurrence frequency is higher and less variable than in the SH. The NH clouds are brighter and extend to lower latitudes than their southern counterparts (e.g. Bailey et al., 2007).

Noctilucent clouds are very sensitive to changes in their environment, such as in changes in the mesospheric water vapor content and temperature or in dynamical parameters, like wave activity (Baumgarten et al., 2010). Even small fluctuations in these variables lead to modifications of the cloud brightness and frequency of occurrence of NLCs (Rapp et al., 2002; Megner, 2011; Megner et al., 2016).

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* Corresponding author.

E-mail addresses: maartje.kuilman@misu.su.se (M. Kuilman), bodil@misu.su.se (B. Karlsson), susanne.benze@misu.su.se (S. Benze), linda.megner@misu.su.se (L. Megner).

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NLC variability is driven by various atmospheric processes such as the solar cycle (DeLand et al., 2003; Hervig et al., 2016b), gravity waves (Siskind et al., 2003; Gerrard et al., 2004; Chandran et al., 2009), planetary waves (Merkel et al., 2003, 2008; Von Savigny et al., 2007; Pendlebury, 2012; Siskind and McCormack, 2014) and interhemispheric coupling (Karlsson et al., 2007, 2009; Karlsson and Becker, 2016). Many of these processes are initiated in the lower atmosphere and may result in changes in the strength of the residual flow itself, or have a more direct effect on the ice particles in the forms of heating and cooling patterns related to wave crests and troughs, as well as generation of turbulence.

In addition, co-existence and interactions between the different processes make it hard to pinpoint specific sources of variability. For example, the residual circulation drives down the temperature in the summer polar mesosphere, supplies the region with water vapor and slows down the sedimentation of the NLC particles, which leads to larger growth. This means that a weakening in strength of the circulation results in a decrease in water vapor and in higher temperatures. Solar radiation has a similar effect: at solar maxima, most of the middle atmosphere is heated and at the same time, more water vapor is destroyed by the increased Lyman alpha radiation in the upper middle atmosphere (Marsh et al., 2007). Gravity waves would in general be expected to contribute to a stronger residual flow, but may also have a destructing in-situ effect on cloud brightness (Chu et al., 2009).

There are a number of factors to consider when it comes to NLC variability. What are the mechanisms? Which mechanism is dominant at a specific time? How much of the variability observed in NLCs is driven by processes in the lower atmosphere? The use of global climate models for studying NLC variability opens up possibilities when it comes to addressing these questions, as seen in Lübken and Berger (2011) and Bardeen et al. (2010).

In this study, it is explored how a comprehensive state-of-the-art general circulation model - in which NLCs are represented in terms of a simple model - can be used in studies of large-scale zonally averaged NLC variability. The approach is inspired by earlier work of Merkel et al. (2009), who demonstrated - using output from the Whole-Atmosphere Community Climate Model (WACCM) - that an empirically based model of NLCs functions rather well in reproducing the bulk features in the clouds. The advantage of modeling clouds with a simple model rather than using a full microphysical cloud model is that the computational cost is comparably low.

We also acknowledge the work of Berger and Lübken (2015), in which a sophisticated ice microphysics scheme MIMAS (Mesospheric Ice Microphysics and Transport) coupled with the Leibniz-Institute Middle Atmosphere (LIMA) model (see e.g. Lübken et al., 2013), was used to investigate trends in the July summer mesopause. They found a good agreement between their model outcome and the Solar Backscatter Ultraviolet Radiometer (SBUV; see section 2.3) -instrument on the Aura satellite.

It should be emphasized that our focus is on studying the zonal mean variability and climatology of the NLCs and not the absolute ice mass. For this purpose, we use a version of the extended Canadian Middle Atmosphere Model (CMAM; Fomichev et al., 2002), which is nudged to reanalysis data (e.g. McLandress et al., 2014): CMAM30. Nudging entails that the dynamical variables of a Global Climate Model -in this case CMAM-are adjusted with meteorological reanalysis data in order to provide a representation of the atmosphere at a specific time.

The model is described in Section 2, along with brief summaries of the satellite data from the Optical Spectrograph and InfraRed Imagining System (OSIRIS) instrument on the Odin satellite (Llewellyn et al., 2004), the Solar Occultation for Ice Experiment (SOFIE) instrument on the Aeronomy of Ice in the Mesosphere (AIM) satellite (Russell et al., 2009) and the Solar Backscatter Ultraviolet Radiometer (SBUV) (DeLand and Thomas, 2015), which we use to examine our modeled NLCs. In Section 3, the NLC model is described and discussed in parallel with comparisons to satellite observations. The conclusions are discussed in section 4.

2. Data

2.1. CMAM30

CMAM30 is a comprehensive state-of-the-art chemistry-climate model (Beagley et al., 1997; De Grandpré et al., 2000). The model yields a 30-year retrospective dataset extending from 1979 to 2009. It has a spatial resolution just under 6° in latitude and longitude.

The model is nudged, i.e. winds, temperatures and also water vapor and ozone are relaxed to the Interim reanalysis product from the European Centre for Medium-Range Weather Forecasts (ERA-Interim; Simmons et al., 2007). The ERA-Interim data are produced by a high-resolution model that assimilates past measurements, in this way yielding a representation of the atmospheric state over a given time period. Reanalysis models reconstruct many physical schemes in a very sophisticated manner (such as convection or land-surface interaction). However, they generally do not include small-scale atmospheric processes, such as gravity wave momentum deposition, that are necessary for an accurate representation of the middle atmosphere. CMAM30 is nudged to ERA-Interim products up to 1 hPa on large spatial scales (<T21) with a Newtonian relaxation timescale of 24 h. The data is sampled every 6th hour and interpolated to a set constant pressure surfaces, which are close to the underlying model levels. It has been noticed that in upper stratosphere, the data used for nudging contain some temporal discontinuities, resulting from inhomogeneities in the observational data. These temporal discontinuities are removed from the model data, using a specific procedure explained by McLandress et al. (2014). Above 1 hPa, the model is free running.

Chemistry-climate models (CCMs) with fully interactive chemistry are able to simulate many atmospheric processes, but they do not entail the day-to-day variability. CMAM30 brings these two approaches together: it is a comprehensive chemistry-climate model, which is nudged to ERA-Interim data. This means that CMAM30 should provide the observed variability of the winds and temperatures below 1 hPa, along with trace gas information that is consistent with these fields (e.g. Shepherd et al., 2014a; Hegglin et al., 2014).

There are two versions of CMAM30: the regular and the extended CMAM30. The extended version of CMAM30 (Beagley et al., 2000, 2010; Fomichev et al., 2002; McLandress et al., 2006) is based on the regular version of CMAM30 and reaches up to a height of approximately 210 km and has 87 vertical levels. It is one of the first general circulation models that extends from the ground up to the thermosphere. We will refer to the extended version of CMAM30 as ‘CMAM30ext’.

The main difference between the regular and extended version of CMAM is that the regular version of the CMAM incorporates an artificial damping layer, to prevent false reflections of vertically propagating waves. This ‘sponge layer’ can feed back on the circulation if an imposed force, for example gravity-wave drag, is applied within or near it (Shepherd et al., 1996). A lid at 95 km then causes problems for simulating the MLT region. The primary rationale for the extended version is to investigate physical and dynamical processes in the mesosphere as well as the lower thermosphere without the artificial effects of such a layer, which can change the circulation in an unrealistic manner. In the extended version, the molecular diffusion and ion drag dissipate upward propagating waves and thus provide a natural sponge (Fomichev et al., 2002).

The CMAM30ext includes both the effects of the unresolved orographic and non-orographic gravity waves (Fomichev et al., 2002). The unresolved orographic gravity waves are treated using the parameterization of McFarlane (1987), while the non-orographic gravity waves are treated using the Doppler spread parameterization of Hines (1997a; b).

Further details on the extended CMAM can be found in Fomichev et al. (2002), Scinocca et al. (2008), McLandress et al. (2014) and Shepherd et al. (2014a).