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Temporal and spatial characteristics of the formation of strong noctilucent clouds

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ABSTRACT

The 3-D Lagrangian model LIMA/ICE is used to track ice particles forming noctilucent clouds (NLC). Fifty strong NLC events at three different latitudes are analyzed. Visible particles are traced back to their nucleation sites as well as traced forward until sublimation. Particle nucleation occurs in bursts within areas of high supersaturation. We characterize NLC particle growth and vertical transport: Slow growth occurs below the mesopause up to ≈ 6 h before observation. It is followed by rapid growth within the high water vapor zone around 83 km during phases of upward winds. At the same time temperature perturbations in these cold phases of waves lead to a high supersaturation. Sublimation occurs quickly after maximum brightness, since sedimentation into subsaturated altitudes is accelerated by downward winds. The duration of particle visibility ($\beta > 10\%$ of observed backscatter) is only ≈ 5 h. The mean particle age of all NLC events at 69°N is around 36 h, but particle age varies by more than 24 h for the different events studied. Although the age of particles in strong NLC depends on latitude, the visibility period does not. The brightness of strong NLC depends mainly on background conditions during the last 3 h before observation. This implies that local measurements, e.g. by lidar, are representative for the morphology of strong NLC on scales of several hundred kilometers.

1. Introduction

1.1. Motivation

Noctilucent clouds (NLC) are the manifestation of ice particles in the polar summer mesosphere at altitudes of ≈ 83 km. In this region of the atmosphere, ice can only nucleate at temperatures below ≈ 150 K. This is often fulfilled around the mesopause from June to mid of August at northern polar latitudes, with a 6 month offset for SH. NLC may be seen by the naked eye at times when the middle atmosphere is still illuminated by the sun and the observer's position is in nautical twilight (e.g. Jesse, 1889). In the northern hemisphere this typically happens in the latitude band 50–65°N. A method for detecting NLC which does not depend on solar illumination is ground-based lidar measurements (e.g. Fiedler et al., 2009). NLC are also observable from satellites like the Aeronomy of Ice in the Mesosphere (AIM) satellite, which detects mesospheric ice by scattering of sunlight in the UV region (Cloud Imaging and Particle Size, CIPS) and by extinction of direct sunlight through the atmosphere at multiple wavelengths (Solar Occultation For Ice Experiment, SOFIE) (McClintock et al., 2009; Hervig et al., 2009; Russell et al., 2009).

The size of these particles (≤ 100 nm) is much smaller than that of tropospheric ice clouds (Thomas and McKay, 1985). Since the scattering cross section of particles in this size regime at optical wavelengths is roughly proportional to r^5, mostly the larger particles ($r > 20$ nm) are visible to observers as well as optical instruments (i.e. cameras, lidars, spectrometers). Other instruments (i.e. radar, mass spectrometers, solar occultation) are capable of observing smaller ice particles that play a major role in generating polar mesospheric summer echoes (PMSE) which are often found together with NLC (e.g. Nussbaumer et al., 1996; Gumbel and Witt, 2001; Rapp and Lübken, 2004; Li et al., 2010; Kaifler et al., 2011).

Right now, there is no experimental method to directly trace the history of individual ice particles forming a noctilucent cloud. Only the ice clouds are temporarily observable as well as wind and temperature, within limits. A main reason for studying NLC is that they indicate extreme background conditions and are much easier to detect than those conditions themselves. Model studies suggest that NLC are formed at least several hundred kilometers away from the place of observation (e.g. Turco et al., 1982; von Zahn and Berger, 2003; Stevens et al., 2007; Merkel et al., 2009; Bardeen et al., 2010; Megner, 2011). Thus a detailed understanding of ice growth processes and origins is required to infer background conditions from NLC observations. Therefore we use modeling studies to examine origins, growth, and sublimation conditions of observed ice particles, as well as the factors determining their evolution.

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1.2. Model description

In this study we use the Leibniz-Institute Middle Atmosphere (LIMA) model, a general circulation model with special emphasis on the mesosphere (Berger, 2008). LIMA adapts ECMWF reanalysis data in order to incorporate lower atmosphere effects. Thus it shows interannual variations like the solar cycle and trends, e.g. in temperature (Lübken et al., 2009). LIMA uses a triangular grid with a horizontal resolution of 110 km and a time step of 150 s.

There have been several model studies of NLC using the Community Aerosol and Radiation Model for Atmospheres (CARMA) on various circulation models. Examples are the Whole Atmosphere Community Climate Model (WACCM) (Bardeen et al., 2010; Merkel et al., 2009); the Navy Operational Global Atmospheric Prediction System (NOGAPS) (Stevens et al., 2010); and the Canadian Middle Atmosphere Model (CMAM) (Megner, 2011).

Our approach has some advantages compared to previous studies: While Bardeen et al. (2010) and Merkel et al. (2009) also use 3-D aerosol models that allow a continuous simulation over a time period of several months, similar to our approach, our Lagrangian model computes the particle trajectories in the same model run. This makes our model approach well suited for simultaneously investigating single particle evolution and ice development of the whole cloud. Since the cloud evolution strongly depends on the smaller scale variations in the atmosphere, our more realistic modeling of the background fields compared to COMMA/IAP is beneficial (Chandran et al., 2012; Berger and von Zahn, 2007).

In Fig. 1 we show the wind structure from LIMA compared with MF radar measurements at Andenes in Northern Norway (69°19′N, 16°18′E), similar to the data presented in Hoffmann et al. (2010). The radar measurements are 2 day mean winds after removing the 12 h and 24 h tides. These are compared with diurnal mean LIMA winds at the grid point nearest to Andenes. Since only ice clouds in the central NLC season are studied, we limit the wind comparison to the NLC season (June to August) and NLC altitudes (80–92 km). In this period, LIMA zonal winds are in general agreement with radar winds. We note that around 80 km, LIMA overestimates the mean zonal wind by ≈ 15 m/s, which is perhaps caused by deficiencies in the gravity wave parametrization. This deviation is present at most altitudes, but is less pronounced near the mesopause (≈ 90 km). Mean meridional winds agree very well at 83 km, while further up the radar southward wind is stronger by up to ≈ 6 m/s. Radar measurements also show a higher variability compared to LIMA. We discuss the implications of these differences later in Section 3.1.2. Generally, we expect westward transport in LIMA being somewhat too strong, southward transport being slightly too weak. The lower variability in LIMA horizontal winds suggests that vertical wind variations are also underestimated to some extent.

To model noctilucent cloud formation, we employ the three-dimensional Lagrangian ice transport model LIMA/ICE (Lübken et al., 2009). NLC formation is simulated by advecting 40 million condensation nuclei ("dust particles") in wind and temperature fields supplied by LIMA at a time step of 180 seconds. The dust particles range in radius from 1.2 to 3.7 nm, forming the larger

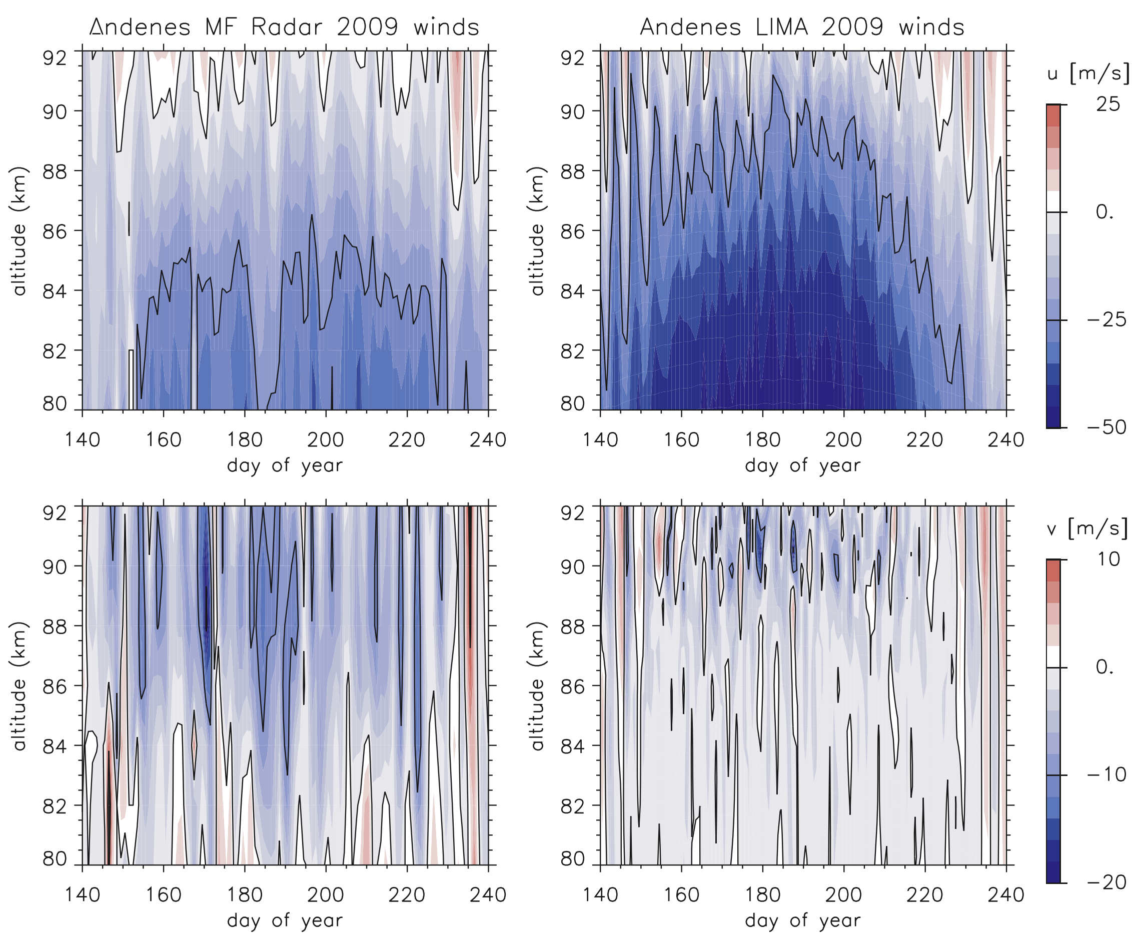

Fig. 1. Summer 2009 wind profiles at Andenes (69°N), zonal (upper) and meridional (lower). Left side: Residual winds of a 2-day fit removing diurnal and semidiurnal tides from MF radar measurements. Right side: diurnal mean LIMA winds.

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