On the early onset of the NLC season 2013 as observed at ALOMAR

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A B S T R A C T

On 21 May the ALOMAR RMR-lidar in Northern Norway detected the first noctilucent clouds (NLC) in 2013. This unusual early NLC onset was accompanied by ~6 K lower temperatures and higher water vapor mixing ratios at NLC altitudes from the end of April until the beginning of June. The zonal mean temperature and dynamic conditions in the Arctic middle atmosphere deviated in spring 2013 significantly from the mean conditions of the last 20 years. Furthermore the planetary wave activity in the high latitude stratosphere was enhanced from 20 April to beginning of May. The colder and wetter upper mesosphere in May 2013 is attributed to this unusual late planetary wave activity in the stratosphere, introducing a strong upwelling in the mesosphere, lower temperatures and an upward transport of water vapor, which finally resulted in earlier existence conditions for mesospheric ice particles. We regard this as a first evidence for intra-hemispheric coupling in the northern hemisphere extending from the stratosphere into the mesopause region. Yet it is unclear whether this is an unusual extreme event or an indicator for a change in the circulation due to the observed long-term cooling of the middle atmosphere.

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1. Introduction

During summer at high latitudes temperatures in the mesopause region fall very low so that water vapor can freeze condense. The results are nanometer sized ice particles in an altitude range between 80 and 90 km, which are visible to ground-based observers at night by scattered sunlight and are thus called noctilucent clouds (NLC). Since the early observations by naked eye more than 125 years ago, NLC are detected by remote sensing and in situ instruments since some decades. While in situ experiments provide snapshots with high temporal resolution (e.g., Gumbel et al., 2011) satellite- and ground-based remote sensing instruments cover larger periods. The longest timeseries of such cloud observations acquired from space is collected by the Solar backscatter ultraviolet (SBUV) satellite instruments starting in 1979. It refers to the brightness and occurrence frequency of polar mesospheric clouds (PMC) which is the notation for NLC when observed from space (e.g., DeLand et al., 2007; Shettle et al., 2009). Lidar observations of NLC on regular basis started in 1994 and provide additionally cloud altitudes with high accuracy (e.g., Thayer et al., 2003; Fiedler et al., 2011).

Polar mesospheric summer echoes (PMSE) are strong radar signals received from the mesopause region. They are caused by electron density irregularities at the Bragg scale which are created due to coupling of electrons to charged aerosols like ice particles. PMSE are sensitive to ice particles of any size, including those which are too small to be detected by lidar. PMSE is an indirect indicator for the presence of ice particles (e.g., Rapp and Lübken, 2004; Kaifler et al., 2011). Mesospheric ice particles are bound to very low temperatures ≤150 K in combination with water vapor mixing ratios of a few ppmv and react extremely sensitive to changes of these parameters (e.g., Turco et al., 1982). For this reason the onset of NLC particle formation is linked to the seasonal variations of temperature and water vapor which themselves are subject to dynamical processes on different scales. A couple of investigations have shown that the onset of mesospheric ice in the southern hemisphere (SH) is controlled by the shift from winter to summer zonal wind flow in the stratosphere and the solar cycle (e.g., Karlsson et al., 2011). For the northern hemisphere (NH) a relationship to the timing of the winter to summer transition was not yet found. In the following we will present such possible link for spring 2013.

2. Data sets

The Rayleigh/Mie/Raman-(RMR-)lidar at the Arctic Lidar Observatory for Middle Atmosphere Research (ALOMAR) facility in Northern Norway (69°N, 16°E) is a sophisticated remote sensing
instrument for climatological studies in the middle atmosphere (von Zahn et al., 2000) and optimized for the detection of NLC. Since 1994 the system is operated on a routine basis during the summer seasons. From the beginning of June until mid-August the data archive contains approx. 5450 h of lidar data, distributed over 20 years. During 2480 h NLC were detected, which is the largest NLC data set acquired by lidar. Details regarding data processing and NLC properties are presented in, e.g., Baumgarten et al. (2008) and Fiedler et al. (2009).

The Middle Atmosphere Alomar Radar System (MAARSY) as well as its precursor, the ALWIN-radar, operate at 53 MHz and observe PMSE on a regular basis since 1999 (Lattek and Bremer, 2013). As the radar operations are weather independent, the onset of the PMSE season is determined very precisely during each year.

The AURA satellite was launched by NASA in 2004 into a near-polar 705 km altitude orbit and is dedicated to monitoring the complex interactions that affect the globe (Schoeberl et al., 2006). One of its instruments is a Microwave Limb Sounder (MLS) for measurements of atmospheric composition, temperature, humidity and cloud ice. It observes thermal microwave emission from Earth’s limb from the ground to ~90 km every ~25 s. We use mesospheric data from MLS to characterize the atmospheric conditions above ALOMAR.

To access the NH global situation during the last 20 years we make use of Modern-Era Retrospective Analysis for research and applications (MERRA) data (Rienecker et al., 2011). The chosen data product (MAI6NVANA) describes the atmosphere on a 3-dimensional grid having 540 longitudes, 361 latitudes, and 72 pressure levels four times per day. The upper level is 1.5 Pa, corresponding to altitudes between ~72 km and ~80 km, depending on season.

3. Results

In 2013 the RMR-lidar detected the first NLC on 21 May. From 16:45 to 17:20 UT an enhanced backscatter signal at 532 nm wavelength was observed at an altitude \( z \approx 83 \) km. The volume backscatter coefficient of NLC particles is a measure for the cloud brightness and defined as

\[
\beta_{\text{NL}}(z) = (R(z) - 1) \times \beta_{\text{M}}(z)
\]

with \( R(z) \) being the backscatter ratio, i.e. the ratio of total signal to molecular signal \( \beta_{\text{M}}(z) \), indicating the presence of aerosol particles. Integrated over the NLC observation period the maximum value of \( \beta_{\text{NL}}(z) \) was \( 0.25 \times 10^{-10} \text{ m}^{-1} \text{ sr}^{-1} \) which is below the faint cloud limit according to the brightness classes used to characterize our multi-year NLC data set (Fiedler et al., 2011). This first detection was no single event as during the following days NLC were observed too (see Fig. 1). All these clouds have \( \beta_{\text{NL}} \) less than \( 4 \times 10^{-10} \text{ m}^{-1} \text{ sr}^{-1} \) which is typical for the beginning of the season.

Fig. 2 shows the seasonal distribution of measurements and NLC occurrence rate for the integrated data set from 1994 to 2013. On average the NLC season above ALOMAR starts at the beginning of June, even though the observation of the first cloud may vary depending on clear sky conditions above the observatory. The detection on 21 May 2013 was the earliest NLC within 20 years. Compared to 2013, where the RMR-lidar measured for 67 h between 21 and 31 May, there are only sporadic measurements during the second half of May in the years before. Thus we cannot rule out such early NLC in the previous years.

Fig. 2 also shows the seasonal behavior of PMSE occurrence rates above ALOMAR. Averaging over 14 years the PMSE season starts on 16 May. The year 2013 with the first PMSE detection on 18 May was therefore not unusual, however the temporal development during the following days was indeed. Within one week the daily PMSE occurrence rate reached already 80%, which is approx. 3 times faster than the mean behavior. This result is statistically robust due to the nearly continuous operation of the radar during May in each year. In summary, the lidar and radar measurements indicate a fast and, for the larger particles, early onset of mesospheric ice in 2013.

To understand the curious appearance we look for the local atmospheric background conditions at NLC altitudes above ALOMAR as provided by the MLS instrument onboard the AURA satellite. The coarse altitude resolution of about 12 km and the temperature accuracy in the mesosphere play a minor role in this context as we aim for differences between individual years. Fig. 3 shows temperature and water vapor at 83 km altitude over ALOMAR for all years from 2005 to 2013. Starting around 20 April, day of year (day) 110, the temperature in 2013 is \( \sim 6 \) K lower compared to the mean. This deviation lasts until the end of May. During spring the water content in the mesopause region is generally increasing which is related to the seasonal change in the wave-driven meridional mass circulation (Lossow et al., 2009). From the beginning of May (day 121) to mid-June 2013 the water vapor mixing ratio is increased by up to 1 ppmv compared to the mean, which is at the beginning of this period a significant enhancement of \( \sim 100\% \). Altogether these deviations from the mean behavior result in more favorable conditions for ice particle formation and existence.

Next, we investigate if these special conditions in spring 2013 appeared only locally. For that MERRA reanalysis data in a 10°
latitude band centered around ALOMAR are used. Fig. 4 shows zonal mean temperature and zonal wind in stratosphere and mesosphere for the last 20 years. Beginning in April the temperature in the stratosphere (mesosphere) was up to 7 K higher (lower) compared to the mean. This behavior is first visible in the stratosphere, followed later by the mesosphere. In 2013 the zonal wind reversal to summer easterly conditions occurred ~10 days later in the stratosphere and did not deviate in the mesosphere in comparison to the mean behavior. However, the reversal was comparatively fast and the wind velocities remain large into the NLC season. Obviously the zonal mean temperature and dynamic conditions in the Arctic middle atmosphere in spring 2013 deviated significantly from the mean conditions of the last 20 years.

To accommodate this large scale character of the phenomenon we calculated the divergence of the Eliassen–Palm flux (EPFD), which is commonly used as a measure for planetary wave activity:

$$\nabla \cdot \mathbf{F} = \frac{1}{R} \frac{\partial [u \mathbf{v}]}{\partial \varphi} + \frac{\partial f}{\partial p} \frac{\partial \Theta}{\partial p}$$

(2)

where $\varphi$ is the latitude, $p$ is the pressure, $u$ and $v$ are the zonal and meridional winds, respectively, $\Theta$ is the potential temperature, $R$ is the Earth's radius, $f$ is the Coriolis parameter and $\mathbf{F}$ is the Eliassen–
Palm flux (cf. Andrews et al., 1987). The primes (′) denote the deviations from the zonal means. Fig. 5 shows EPFD timeseries in the stratosphere from 1994 to 2013, averaged from 64°N to 74°N, as calculated from the MERRA reanalysis data. With the outgoing winter the EPFD is generally decreasing and relaxes towards zero during the second half of May. The year 2013 shows a striking different behavior. From around 20 April (day 110) to the beginning of May the EPFD is up to five times larger than the multi-year mean. It is mainly the heat flux rather than the momentum flux contributing to this enhancement. Moreover, it is the latest period during the last 20 years with such high planetary wave activity in the stratosphere at this latitude band.

4. Discussion and conclusions

We have reported an unusual early onset of the NLC season over ALOMAR in 2013. The first cloud detection on 21 May was about 10 days before the mean beginning of the season as determined from 20 years observations. This exceptional case is supported by the onset of the PMSE season at the same location. It was not earlier compared to the mean but faster regarding the increase of occurrence rates. Apparently the early onset of the season had a larger latitudinal/longitudinal extent as instruments on board the AIM satellite observed the NH 2013 PMC season starting about 8 days earlier than the previous 7 seasons (S.M. Bailey, private communication, 2014).

For the SH a high correlation between the timing of the stratospheric wind reversal to summer conditions and PMC season onset date was reported (Karlsson et al., 2011). This is called intra-hemispheric coupling and the suggested mechanism acts over the impact of eastward gravity wave drag on mesospheric upwelling, causing the cold summer mesopause region. Benze et al. (2012) extended these investigations for the NH. For 28 seasons of SBUV data they found no influence of stratospheric zonal wind reversal on the PMC season onset due to an earlier breakup of the polar vortex and therefore earlier wind reversal compared to the SH.

However, they found the NH PMC onset date to be controlled by changes in SH stratospheric zonal winds. Such inter-hemispheric coupling was first described by Karlsson et al. (2007), who found an anticorrelation between stratospheric temperatures in the winter hemisphere and NLC particle sizes in the summer hemisphere. Following this we have investigated the SH zonal winds in 10 hPa in the 40°S to 60°S latitude band using MERRA reanalysis data. We find during April and May the year 2013 to represent almost the mean behavior of the last 20 years (not shown here). We conclude that inter-hemispheric coupling was not causing the early NLC onset at ALOMAR 2013.

Benze et al. (2012) also found the PMC onset in the NH to be correlated to solar activity, the onset date should be delayed by 7 days at solar maximum compared to minimum. In spring 2013 the Lyman-α flux was \( -4.4 \times 10^{13} \) photons/s/cm² (taken from http://lasp.colorado.edu/lisird/lya/) and hence about 35% of the usual variability range over the solar cycle which would not exclusively explain a ten day earlier NLC onset.

To recall the temporal development of the data shown above: Measurements of temperature and water vapor at NLC altitudes above ALOMAR show that it was colder by \( \sim 6 \) K from 20 April to end of May and the water content was higher from the beginning of May compared to the mean state. Reanalysis data show that NH stratospheric and mesospheric conditions differed significantly from the mean of the last 20 years on large scale. From the same data set an enhanced planetary wave activity from about 20 April to the beginning of May was extracted, which is connected with a dominating zonal wavenumber 2 at the end of April around 69°N (not shown here). Fig. 4 indicates that the winter polar vortex maintained longer than usual, and that the change from westerlies to easterlies associated with the final vortex breakup occurred fast. Additionally the EPFD of 2013 illustrates that this breakup is forced by unusual planetary wave activity.

Merging these facts the following scenario seems to be plausible: The unusual long duration of the polar vortex led to enhanced baroclinity in the mid-latitude upper troposphere/lower stratosphere and, hence, strong planetary wave activity triggering the rapid final vortex breakup process. Then, similar to major stratospheric warming events (e.g., Limpasuvan et al., 2012), the enhanced planetary wave activity and the associated shift in the critical level of gravity wave filtering from upper stratosphere to upper mesosphere led to downwelling in the stratosphere and strong upwelling in the mesosphere causing adiabatic warming and cooling, respectively. The upwelling was responsible for an upward transport of mesospheric water vapor. The rapid change from eastward to westward winds accelerates the reversal to summer conditions due to the induced shift in gravity wave filtering. In summary, favorable conditions for the existence of larger, and hence optically visible, ice particles were present earlier than normal. If these processes had been developed earlier in spring, it probably would not have resulted into early mesospheric ice formation. The temperatures in the mesopause region would have been still too high, and the disturbed temperature and the wind structure relax again towards the mean state.

Hence it was the exact timing, meaning the exceptional late enhanced planetary wave activity connected with the vortex breakup, which initially impacted the temperature state of the NH middle atmosphere and finally caused NLC formation above ALOMAR already in the second half of May. We regard this as a first evidence for intra-hemispheric coupling in the NH, originated in the stratosphere and extending into the mesopause region. The reason for the unusual long duration of the polar vortex is still unclear. In the NH the day of the final vortex breakup does not show a significant trend towards a longer persistence of the polar vortex because of the long-term cooling of the middle atmosphere due to anthropogenic carbon dioxide emissions and polar ozone destructions as found for the SH (e.g., Waugh and Polvani, 2010). Further monitoring is needed to verify whether the cooling of the middle atmosphere could lead to an enhanced probability of early NLC onset events in the NH.

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References


