GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L02805, doi:10.1029/2006GL028106, 2007

On the disappearance of noctilucent clouds during the January 2005 solar proton events

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Received 7 September 2006; revised 18 October 2006; accepted 14 November 2006; published 17 January 2007.

[1] A possible connection between the January 2005 solar proton events (SPEs) and the partial disappearance of Noctilucent clouds (NLCs) in the southern polar mesopause region is studied. Space-borne measurements of the NLC occurrence rate made with SCIAMACHY on Envisat as well as temperature measurements with MLS on Aura are employed. Immediately after the onset of the enhanced solar particle precipitation on January 16, 2005, we observe a severe decrease in the NLC occurrence rate. Between 70°S–80°S the NLC occurrence rate drops from about 80% to less than 20% within the period of enhanced solar proton fluxes. Throughout this period an anti-correlation between NLC occurrence rate and temperatures at NLC altitude is found, and the disappearance of NLCs is apparently caused by increasing temperatures. Potential mechanisms leading to the warming are discussed. **Citation:** von Savigny, C., M. Sinnhuber, H. Bovensmann, J. P. Burrows, M.-B. Kallenrode, and M. Schwartz (2007), On the disappearance of noctilucent clouds during the January 2005 solar proton events, *Geophys. Res. Lett.*, *34*, L02805, doi:10.1029/2006GL028106.

1. Introduction

[2] Noctilucent clouds (NLCs) consist of H_2O ice particles with sizes of up to several tens of nm [e.g., *Rusch et al.*, 1991; *von Savigny et al.*, 2004]. They occur at altitudes of 82–85 km and latitudes poleward of about 55° during about a 12 week period around summer solstice in the summer hemisphere. NLC formation requires temperatures of less than about 150 K. The formation and existence of NLC particles depends sensitively on the thermal conditions and the H_2O abundance in the mesopause region. Any process affecting the temperature field or the ambient H_2O abundance will affect NLC particles. In this context, NLCs are being discussed as early indicators of global change [e.g., *Thomas et al.*, 1989; *von Zahn*, 2003], since enhanced CO_2 concentrations may lead to increased radiative cooling of the mesopause region [*Roble and Dickinson*, 1989]. Furthermore, higher atmospheric CH_4 concentrations may eventually lead to an increase in H_2O at the mesopause. Nadir backscatter measurements of the NLC albedo in the UV-C spectral range [*DeLand et al.*, 2003] with the SBUV (Solar Backscatter Ultraviolet) instruments indeed show indications for a long-term increase of the NLC albedo.

[3] However, little is known about the potential effects of solar energetic particles (SEPs) on NLCs. These particles precipitate into the Earth's polar cap areas leading to ionization and subsequent chemical reactions. The ionization is known to effectively cause the conversion of H_2O to HO_x [e.g., *Crutzen and Solomon*, 1980] which in consequence leads to catalytic O_3 losses. Since O_3 is – beside O_2 – the main solar heating agent in the mesosphere, catalytic O_3 losses lead to a cooling of the affected altitude regions. In the upper mesosphere and thermosphere the produced ions together with perturbed electric fields can lead to Joule heating on the order of a few K day^{-1} at NLC altitude [*Roble et al.*, 1987]. Both the possible removal of H_2O and the temperature increase due to Joule and direct particle heating may affect the formation and existence of NLC particles.

2. Instrumentation

2.1. SCIAMACHY on Envisat

[4] SCIAMACHY, the Scanning Imaging Absorption spectroMeter for Atmospheric CHartographY [*Bovensmann et al.*, 1999] was launched on March 1, 2002 from Kourou (French Guyana) onboard ESA's Envisat spacecraft into a polar, sun-synchronous orbit with a 10:00 a.m. descending node. SCIAMACHY is an 8-channel grating spectrograph covering the 220 – 2380 nm spectral range with a spectral resolution of 0.2 – 1.5 nm and measures solar radiation scattered by and transmitted through the atmosphere in Nadir, solar/lunar occultation and limb-scatter mode. For this study we use limb observations only. In limb mode the atmosphere is scanned from the surface up to tangent heights (TH) of about 92 km in steps of 3.3 km. The field of view is about 2.8 km vertically and 110 km horizontally. At every tangent height step a horizontal scan is performed covering a total distance of about 960 km across viewing direction. In viewing direction horizontal distances of about 400 km are covered.

2.2. MLS on Aura

[5] NASA's Earth Observing System (EOS) Aura satellite was launched 15 July 2004. One of its four instruments is the Microwave Limb Sounder (MLS), a greatly-enhanced follow-on to the MLS instrument onboard the Upper Atmosphere Research Satellite (UARS) that measures millimeter- and submillimeter-wavelength thermal emission from the limb of Earth's atmosphere [*Waters et al.*, 2006]. Aura is in a near-polar, sun-synchronous, 705 km altitude orbit, with a 1:45 p.m. ascending equator-crossing time. The Aura MLS

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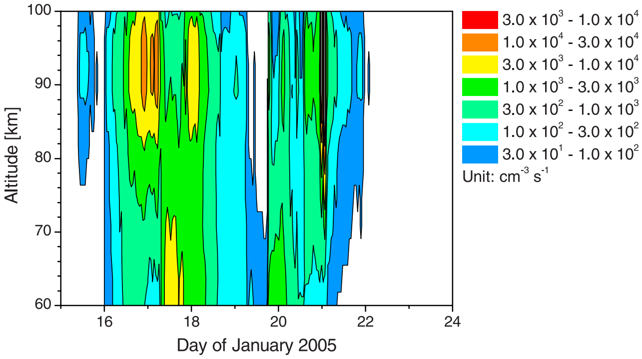

Figure 1. Atmospheric ionization rates due to high-energy solar proton precipitation calculated from GOES proton flux measurements.

fields of view point in the direction of orbital motion and vertically scan the limb in the orbit plane, leading to data coverage from 82°S to 82°N latitude on every orbit.

[6] Vertical profiles are measured every 165 km along the suborbital track and have a horizontal resolution of 165–250 km along-track and 10 km across-track. Here we use the first publicly-released version of the Aura MLS data, v1.51 [*Livesey et al.*, 2006]. Temperature is retrieved from 316 to 0.001 hPa. Validation of the temperature product is still extremely preliminary above 0.1 hPa, but typical estimated precisions (single-profile) vary from 1 K at 0.1 hPa to 2 K at 0.001 hPa [*Froidevaux et al.*, 2006]. The vertical resolution of the v1.51 MLS temperature retrieval ranges from 4 km in the middle stratosphere to more than 12 km in the mesosphere.

3. Methodology

3.1. NLC Detection With SCIAMACHY

[7] NLCs are detected in SCIAMACHY limb radiance profiles using the following approach: Vertical limb radiance gradients (rad(λ, TH) − rad(λ, TH + ΔTH))/Δ TH between adjacent tangent height steps (ΔTH = 3.3 km) are determined for wavelengths of 265 nm and 290 nm and the 75 – 90 km tangent height range. If the vertical gradients exceed the value of 3.0 at both wavelengths for a given limb measurement, then an NLC is identified. Note that the single-scattering Rayleigh-only limb radiance gradient for a kinetic temperature of 120 K is about 2.5 for a 3.3 km tangent height step. Further information on SCIAMACHY NLC observations is given by *von Savigny et al.* [2004].

3.2. Ionization Rates

[8] Particle ionization in the mesosphere has two sources: solar energetic particles (including protons, alpha particles and electrons) precipitating into the polar cap and magnetospheric particles (energetic electrons) precipitating into the auroral oval surrounding the cap. Inspection of SEM data from the Polar Orbiting Environmental Satellite (POES) indicates that particle fluences at the latitudes relevant for this study are strongly dominated by SEPs. Two geomagnetic storms in the second half of Jan 17 and late on Jan 21 resulted in substantial acceleration of energetic electrons. However, since the polar cap expands with increasing Dst index, the bulk of these particles precipitates at lower latitudes than considered in the NLC analysis. Consequently, ionization rates were calculated for the precipitating solar protons only.

[9] In contrast to POES the Geostationary Orbiting Environmental Satellite (GOES) gives a continuous data coverage which despite being made in geostationary orbit nevertheless reflects the particle distribution inside the polar cap. Ionization rates are determined from hourly averaged GOES observations using a Monte Carlo simulation [*Schröter et al.*, 2006]. The derived ionization rate profiles for the January 15 – 24, 2005 period are shown in Figure 1.

4. Results

[10] Figure 2 shows the derived NLC occurrence rates for part of the southern hemisphere 2004/2005 NLC season binned into the 70°S–80°S and the 80°S–90°S latitude bands. Also shown are the calculated ionization rates at an altitude of 82 km. GOES detected the start of the enhanced solar proton flux on January 16 at 02:10 UTC. The NLC occurrence rates before January 16 were nearly constant for the previous 4 weeks at about 90% for the 80°S–90°S latitude band and about 75% for the 70°S–80°S latitude band. After the onset of the enhanced high energy particle precipitation the NLC occurrence rate in both latitude bands decreases significantly during the following days. For the 70°S–80°S latitude band the occurrence rate drops from about 75% on January 16 to less than 15% on January 22, i.e., within a period of only 6 days, which coincides exactly with the period of the enhanced atmospheric ionization. After the end of the enhanced proton precipitation the NLC occurrence rate recovers again to the original values of about 90% between 80°S–90°S, whereas at latitudes between 70°S and 80°S a complete recovery is not observed.

[11] The disappearance of the NLCs may be in principle due to two different processes: (1) a decrease in the H_2O abundance, and (2) increasing temperatures. Unfortunately measurements of H_2O profiles in the upper mesosphere regions are presently not available. However, continuous

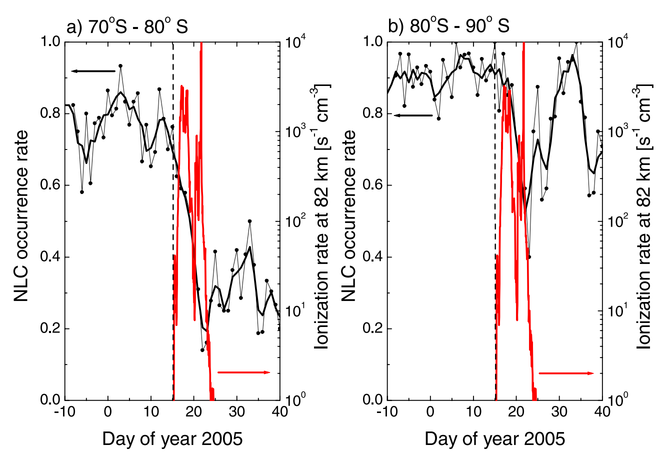

Figure 2. Zonally averaged NLC occurrence rates for different latitude bands and the southern hemisphere NLC season 2004/2005 (left abscissa/grey and black lines), and ionization rates at 82 km (right abscissa/red lines). The solid black lines show the NLC occurrence rates smoothed with a

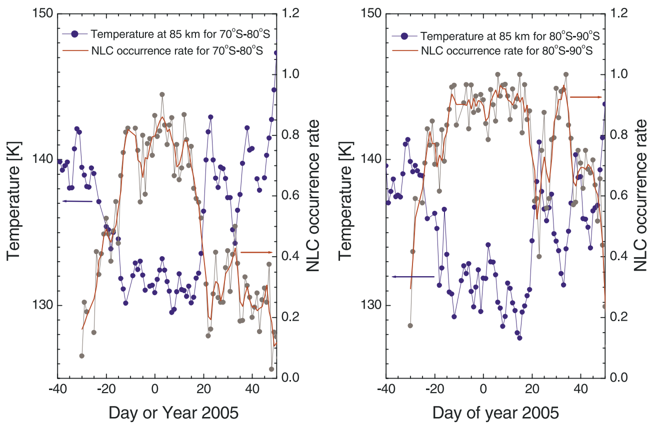

Figure 3. Comparison of NLC occurrence rates and zonally averaged MLS temperatures at 85 km for different latitude bands.

temperature measurements are available from MLS/Aura. A comparison of the NLC occurrence rates with zonally averaged temperatures at an altitude of 85 km as measured with Aura/MLS is shown in Figure 3. We observe an anti-correlation between the NLC occurrence rate and temperature with a correlation coefficient of −0.60 for the 70°S–80°S latitude band and of −0.59 for the 80°S–90°S latitude band. The temperatures were also relatively stable during about 4 weeks before the SPE, with slightly lower values for the 80°S–90°S latitude bin. The temperatures for both latitude bins rise with an average rate of about 2 K day^{-1} during the 6 days with enhanced solar proton fluxes. Note, that because the vertical resolution of the MLS temperature profiles is only about 12 km in the upper mesosphere, the estimated warming rates do not represent 85 km altitude, but a wider altitude range.

[12] Figure 4 shows the longitudinal and temporal variation of the temperature at 86 km altitude and latitudes of 70°S and 80°S. During the days before January 15 the mesopause temperature field is characterized by a stationary planetary wave with wavenumber 1 and amplitude of 2–3 K. Beginning on January 17/18 the temperature increases more rapidly, and the sudden temperature increase occurs first at longitudes of about 100°E, which roughly corresponds to the longitude of the geomagnetic pole (130°E). This may be an indication that the temperature increase is to a certain extent caused by the precipitating protons.

5. Discussion

[13] There are several possible mechanisms that may cause the disappearance of the NLCs. Due to the anti-correlation between NLC occurrence rate and temperature, the temperature increase appears to be the main driver for the depletion of NLCs, and not a reduction in H_2O. In principle the NLC depletion may be a consequence of the sublimation of the optically visible NLC particles in combination with the sublimation of the nucleating particles, which are still below our detection threshold and which would have formed the detectable part of the NLC in the following days. Furthermore the chemical conversion of H_2O to HO_x and subsequent sublimation of NLC may also lead to a reduction in the NLC occurrence rate. However, this mechanism seems unlikely, since a massive removal of H_2O would cause the disappearance of NLCs within hours [*Rapp et al.*, 2002].

[14] Joule heating will occur in the lower thermosphere and mesopause region to some extent as a consequence of the enhanced ionization, and may contribute to the observed temperature increase. According to *Roble et al.* [1987] Joule heating rates on the order of a few K day^{-1} occurred, e.g., during the July 1982 and the August 1972 SPEs. Particle heating due to collisions of the high-energy particles may also contribute. Furthermore, the changes in the mesospheric temperature field caused by the catalytic O_3 destruction may also cause a decrease in the vertical winds (C. Jackman and R. Roble, personal communication, 2006), thereby reducing the adiabatic cooling. All of these mechanisms can in principle lead to a warming of the mesopause region, but at present we cannot say with certainty whether the temperature increase and the associated decrease in NLC occurrence rates is a consequence of one or more of these processes. Strictly speaking, the possibility cannot be excluded, that the warming was caused by a planetary wave perturbation, which is not related to the SPE at all.

[15] The catalytic O_3 loss caused by conversion of H_2O to HO_x may in principle cool the affected regions. However, GOMOS/Envisat measurements in the northern hemisphere showed that at altitudes above 80 km the SPE-produced HO_x leads to negligible O_3 losses [*Seppälä et al.*, 2006]. Significant O_3 losses were only observed below 80 km. The effect in the southern, i.e., summer hemisphere is expected to be significantly smaller, because the ambient H_2O abundances are lower in the continuously illuminated summer hemisphere [e.g., *Solomon et al.*, 1983].

[16] In order to check whether a severe depletion of NLCs also occurred in other southern hemisphere NLC seasons we analyzed all available SCIAMACHY measurements between 2002 and 2006 (see Figure 5). There is strong inter-annual variability and although we observe a significant decrease in NLC occurrence rates also during, e.g., the 2003/2004 NLC season (between days 10–20), the decrease in January 2005 from about 80% to less than 20% within a period of 6 days is unique. In this context NLC measurements with the Student Nitric Oxide Explorer (SNOE) [*Bailey et al.*, 2005] for NLC seasons between 1998 and 2003 show partly strong variations in the NLC occurrence rates. Yet, a reduction as strong and rapid as seen during the January 2005 SPE is not observed.

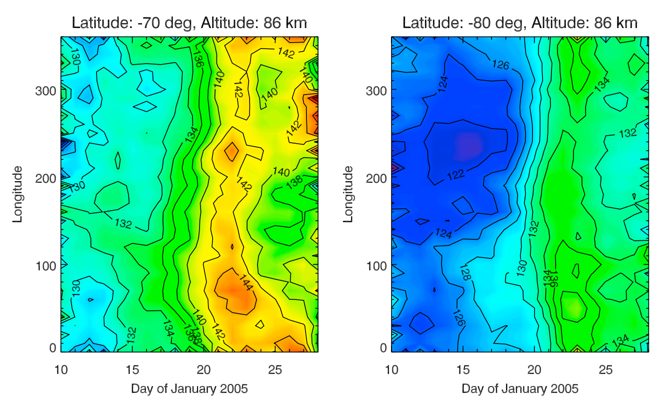

Figure 4. Longitudinal and temporal variation of the temperature at 70°S/80°S latitude and 86 km altitude.

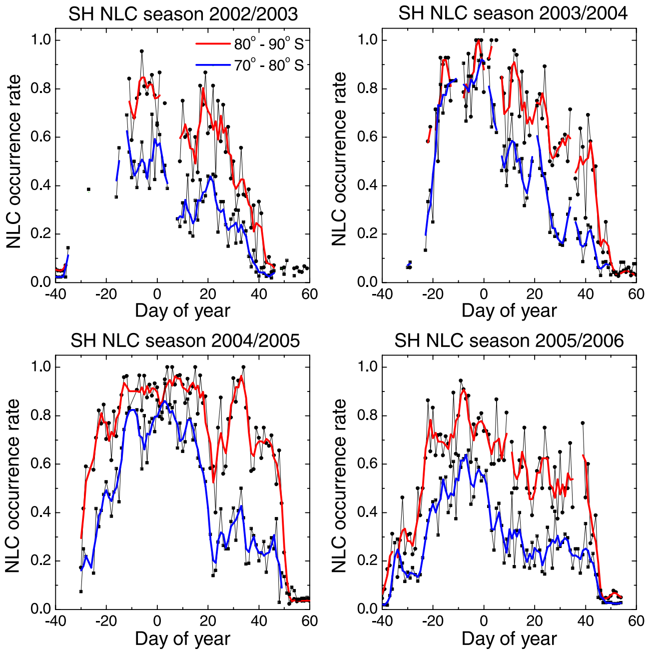

Figure 5. Zonally averaged NLC occurrence rates between 70°S and 80°S (solid circles) and 80°S and 90°S (open squares) for different years. The thick solid lines are 3-day running mean values. The gaps are due to

[17] SNOE NLC measurements are also available during July 2000, when another large SPE occurred. On July 14/15 GOES measured enhanced proton fluxes with a maximum flux of 24000 pfu (proton flux units). The SNOE NLC occurrence rates do not show a very strong signature in mid-July 2000 that may be a consequence of the energetic particle precipitation, although it cannot be excluded that a decline of the NLC occurrence rate at 70 ± 5°N may be related to the SPE. Possible reasons, why the July 2000 SPE does not cause a severe reduction in the SNOE NLC occurrence rates are: (1) the baseline temperature is low enough, so that a temperature increase on the order of several K does not lead to a strong reduction in the observed NLC occurrence rates; and (2) the ionization was not as strong. In fact, the average ionization rate at 82 km for the January 2005 event is comparable to that in July 2000 while, owing to the longer duration, the time integrated ionization rate is about 70% larger.

[18] An important implication of the potential impact of SPEs on the occurrence of NLCs is that it may contribute to the observed solar cycle variation of NLC properties [e.g., *DeLand et al.*, 2003], because SPEs occur more frequently during solar maximum.

6. Conclusion

[19] Although we cannot state with certainty what mechanism leads to the temperature enhancements at the polar summer mesopause region during and after the solar particle precipitation, there are several indications, that a causal relationship exists between the energetic particles and temperature enhancements as well as the disappearance of NLCs. Detailed model simulations are required in order to investigate the impact of each potential mechanism. A better understanding of the potential impact of solar proton events as well as energetic electron events is required, particularly since SPEs occur more frequently during solar maximum, and a solar cycle variation in NLC occurrence frequencies or NLC albedos may be introduced.

[20] **Acknowledgments.** We thank C. Jackman, R. Morris, M. Rapp, G. Rohen, and W. Singer for helpful discussions. This work was supported by the German Ministry of Education and Research (BMBF) and the German Aerospace Center (DLR) under grant 50EE0027, as well as by the University of Bremen. SCIAMACHY is jointly funded by Germany, the Netherlands, and Belgium.

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