LIMA MODEL TRENDS OF MESOSPHERIC ICE LAYERS AND COMPARISON WITH LIDAR OBSERVATIONS AT ALOMAR

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ABSTRACT

LIMA simulations of mesospheric temperatures at mid and polar latitudes in summer are used to study the impact on mesospheric ice layers known as noctilucent clouds (NLC) or polar mesospheric clouds (PMC). A small but significant temperature decrease at NLC altitudes (83 km) causes an increase in occurrence rates and brightness, whereas the impact on mean altitudes is small. The temperature trend changes sign in the mid 1990s. The accidental coincidence of low temperatures and solar cycle minimum in the mid 1990s leads to an intensive period of NLC. The current version of LIMA does not include greenhouse gas trends in the mesosphere but adapts to ECMWF up to ∼35 km. Cooling in the stratosphere leads to a shrinking and associated cooling in the mesosphere which in turn results in ice layer trends. Indeed, long term observations of PMC by satellites show a trend consistent with LIMA. In this paper we compare LIMA results in detail with lidar observations at ALOMAR (69°N). Both LIMA and lidar observations show very persistent NLC altitudes. Occurrence rates are also in nice agreement. For example, the occurrence rate tendency (namely whether they increase or decrease from one year to the next) is the same in 10 out of 11 years. The magnitude of the increase/decrease may differ, however. This is attributed to differences in sampling, averaging, consideration of instrumental sensitivity etc. There is no significant correlation of occurrence rates and Ly_α, neither in LIMA nor in lidar NLC. Ly_α affects water vapor but the influence on temperatures at NLC altitudes is presumably small such that year-to-year variations caused by natural variability overwhelm.

Key words: Noctilucent clouds; summer mesopause ; trends ; solar cycle.

1. INTRODUCTION

Ice clouds in the summer polar mesopause region are considered to be sensitive tracers for long term variations caused by anthropogenic influences and solar cycle. These clouds are known as noctilucent clouds (NLC) or polar mesospheric clouds (PMC). Indeed, solar cycle modulations and a long term increase have been observed by SBUV instruments (Solar Backscatter in the Ultraviolet) which operate on various satellites since 28 years [8, 17]. By applying our LIMA/ice model (see below) we have shown in a recent paper that a major part of these variations comes from temperature trends induced by stratospheric changes, and by solar cycle modulation of water vapor [15] (hereafter referred to as LBB09). Regarding lidar observations of NLC the longest record comes from a RMR-lidar (Rayleigh/Mie/Raman) located at ALOMAR (Arctic Lidar Observatory for Middle Atmosphere Research, 69°N). A detailed description of this lidar and results on long term variations have recently been published by Fiedler et al. [9]. In this paper we expand the analysis performed in LBB09 by considering lower latitudes (54°N) and by comparing with lidar observations at ALOMAR.

2. ICE CLOUD MODELING WITH LIMA/ICE

LIMA (Leibniz-Institute Middle Atmosphere model) is a new general circulation model from 0 to 150 km which concentrates on the thermal structure around mesopause altitudes [4]. LIMA applies a triangular horizontal grid structure with 41804 grid points in every horizontal layer ($\Delta\ x \sim \Delta\ y$ ∼110 km) and adapts to tropospheric and lower stratospheric data from ECMWF (European Center for Medium-Range Weather Forecasts). A 3-d Lagrangian ice transport model is superimposed on LIMA to study the formation and life cycle of ice particles. 40 million condensation nuclei (CN) are transported in LIMA by the background winds, particle eddy diffusion, and sedimentation. Ice particles form and sublimate according to the degree of saturation. The combination of the Lagrangian ice transport model with LIMA background conditions is called LIMA/ice. More details about LIMA/ice and comparisons with observations have been published in the literature [5, 14, 4, 15]. In general there is good agreement between model and observations. In Figure 1 we show occurrence rates from LIMA/ice. Ice layers appear only in the summer season and only poleward of ∼55°N. The frequency increases with latitude. The general morphology shown in Figure 1 is in perfect agreement with ground based and satellite borne measurements, see for example Bailey et al. [2].

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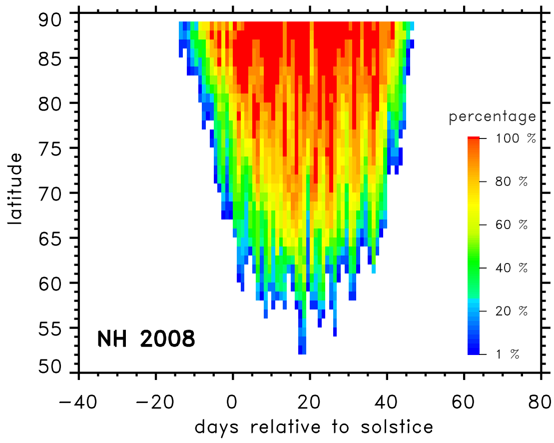

Figure 1. Occurrence rates of NLC from LIMA/ice at a specific longitude (0°E) as a function of season and latitude.

LIMA/ice results are now available from 1961 to 2008, i. e., we have 48 years of distributions similar to that shown in Figure 1. It is important to notice that the concentration of infrared active gases such as CO_2, O_3, and CH_4 is kept constant in the model. In other words, there is no long term anthropogenic variation of greenhouse gases in the current version of LIMA. For H_2O we use the same profile in mid May for all 48 years, which is then exposed to varying Ly_α radiation, background temperatures, transport etc, and also feeds back with ice particles. H_2O therefore varies in time although the profile before the NLC season is the same in all years. All long term variations of mesospheric ice layers observed in the model must ultimately come from the stratosphere (or below) or from solar cycle and indirect effects on water vapor.

3. TEMPERATURE TRENDS

In Figure 2 we show seasonal and zonal mean temperatures from LIMA at 83 km and 42 km, respectively. Temperatures decrease until the mid 1990s except for a peak in 1975/76 which is due a bias in ECMWF probably caused by errors in satellite measurements [11]. Ignoring these outliers the total variation in temperatures at 83 km is only ∼3 K. As has been shown in LBB09 this is sufficient to cause significant changes in PMC occurrence frequency and brightness, and to a lesser extent also in altitude. For comparison we also show solar cycle variations in terms of Ly_α intensity in units of 10^{11} photons/($cm^2 \cdot s$). The temperature minimum in the mid 1990s accidentally coincides with a period of minimum solar activity. This causes relatively large concentrations of water vapor which (together with low temperatures) leads to a period of very bright and frequent PMC. Indeed, ground based and satellite borne instruments detected record high PMC parameters in the mid 1990s [9, 18, 7].

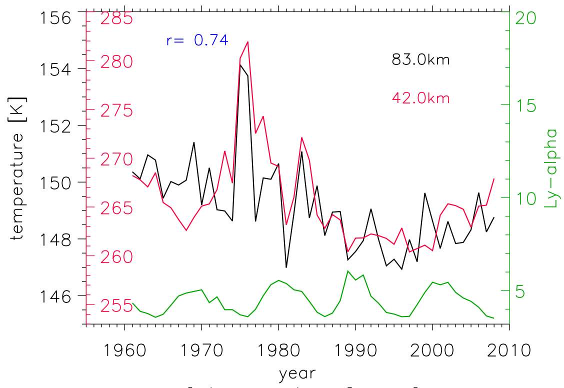

Figure 2. Seasonal (summer) and zonal mean temperatures at NLC heights (83 km, black) in comparison with the upper stratosphere (42 km, red). There is a strong correlation (r=0.74) between both time series. The high temperatures in 1975/76 are due to a bias in ECMWF. Ly_α is shown for comparison (right scale).

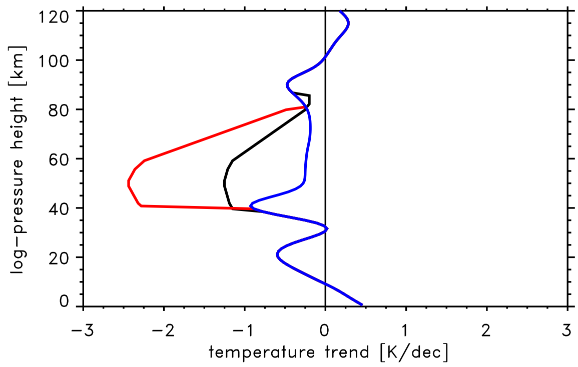

Figure 3. Temperature trends at Kühlungsborn (54°N) as a function of log-pressure altitudes. Blue: results from LIMA. For demonstration purposes temperature trends were added in the mesosphere, namely according to Garcia et al., 2007 (black), and accounting for phase height measurements from Bremer and Berger, 2007 (red line).

In Figure 2 there is a strong correlation between temperatures at NLC heights and those in the upper stratosphere. This supports the idea that stratospheric processes are responsible for temperature changes at PMC altitudes. The outliers in 1975/76 provide an unintended experiment demonstrating this close relationship. The temperature increase in these years directly leads to corresponding increases at 83 km and, furthermore, causes corresponding outliers in PMC parameters (see LBB09).

In Figure 3 we show trends of zonal mean temperatures at 54°N as a function of log-pressure altitudes $z_p = \ln(p(z)/p_\circ) \cdot H_p$. These trends directly reflect the physical cooling mechanisms, namely radiation and adiabatic cooling due to dynamics. Corresponding Figures for 69°N are presented in LBB09. As expected the cooling trend in the mesosphere is rather small since there is no trend in greenhouse gases in the current version of LIMA. Temperature trends in the troposphere and

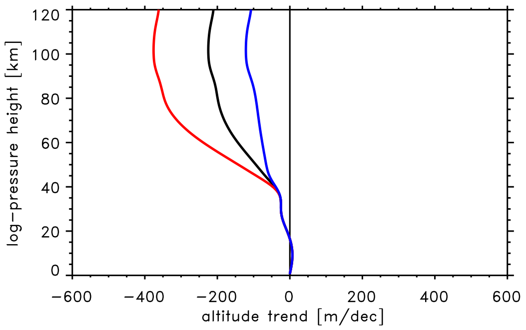

Figure 4. Trend of geometric altitudes at Kühlungsborn (54°N) as a function of log-pressure. Negative values indicate a shrinking of the atmosphere. For different curves: see Figure 3.

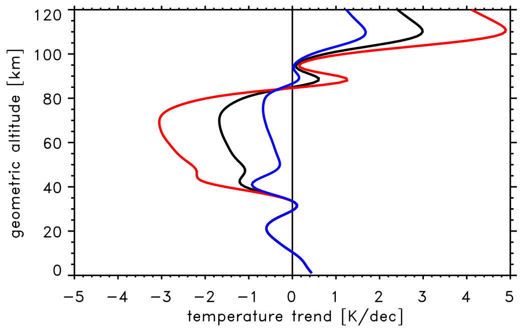

Figure 5. Temperature trends at Kühlungsborn (54°N) as a function of geometric altitude. For different curves: see Figure 3.

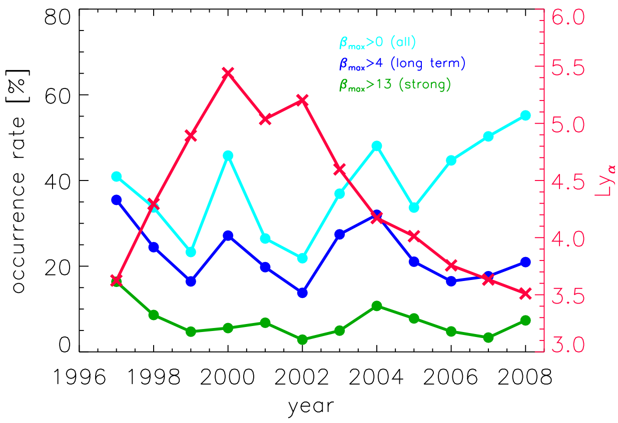

Figure 6. Occurrence rate of NLC observed by the RMR lidar at ALOMAR for 3 different β thresholds (see inlet). More details are given in the text. Ly_α is also shown (red curve, right axis) as an indication of solar activity.

lower stratosphere shown in Figure 3 are due to trends in ECMWF. In Figure 3 we have added temperature trends in the mesosphere typically observed in global circulation models [1, 10]. Furthermore, we have added temperature trends consistent with phase height measurements at 54°N [6].

The stratospheric cooling leads to a shrinking of the atmosphere such that the geometric altitude of a given pressure level in the mesosphere decreases. The corresponding trends of geometric altitudes are shown in Figure 4. At NLC heights the atmosphere shrinks by approximately 100 m/decade. Adding temperature trends consistent with GCM modeling and phase height observations, respectively, leads to a shrinking of up to ~200 m/dec and 350 m/dec in the upper mesosphere. The latter has lead to a descent of the reflection height of radio waves by ~1.4 km in the last 40 years [6].

Since the temperature gradient is negative in the mesosphere a shrinking of the atmosphere leads to a cooling at a given geometrical height. This adds to the cooling rates shown in Figure 3. The total cooling rates at 54°N as a function of geometrical altitudes are shown in Figure 5. Although no greenhouse gas trends are present in LIMA we find a cooling of approximately -0.65 K/dec at NLC heights. This is slightly smaller compared to high latitudes (69°N:-0.8 K/dec) which is consistent with satellite observations of PMC. These show an intensification of PMC occurrence rate and brightness trends with increasing latitude [8, 17]. Taking into account additional temperature trends consistent with GCM modeling and phase height observations (see above), we arrive at total cooling rates of up to -1.7 K/decade and -3 K/decade, respectively, in the mesosphere. At NLC heights, however, the influence of these additional cooling rates decreases drastically and reduces to the LIMA trends. This implies that considering greenhouse gas trends in LIMA in the future will presumably not alter the trends at NLC heights. Therefore, the results on temperature trends in the upper mesosphere and corresponding variations in PMC parameters presented in this paper and in LBB09 will presumably not change significantly when greenhouse gas trends are included in LIMA/ice.

4. NLC DATA FROM RMR LIDAR AT ALOMAR

4.1. Occurrence rates

Fiedler et al. [9] have recently presented a comprehensive analysis of NLC observations performed at ALOMAR from 1998 until 2007. We refer to this paper regarding details of the data analysis and definitions of backscatter coefficients (β), occurrence frequencies, NLC altitudes etc. Including 2008 a total of 3660 hours of lidar observations took place during the NLC season (1. June until 15 August), whereof 1455 hours showed NLC. In Figure 6 we present an update of the occurrence rates from ALOMAR for various β thresholds given in units of 10^{-10}/(m·sr). These thresholds present instrumental limitations ($\beta > 0$) varying in time due to experimental improvements, a long term lower limit ($\beta > 4$), and strong NLC ($\beta > 13$). For comparison we also show solar cycle variation in terms of Ly_α. Note that the occurrence rates for $\beta > 4$ and $\beta > 13$ (i. e., those which are not affected by instrumental improvements) show record high levels at the beginning of observations in 1997. This con-

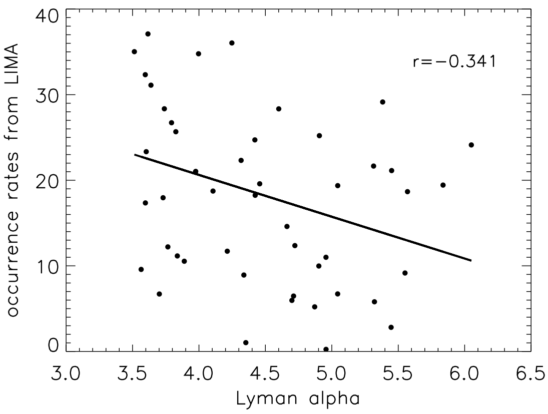

Figure 7. Occurrence rates of NLC at 69°N from LIMA/ice as a function of Ly_α.

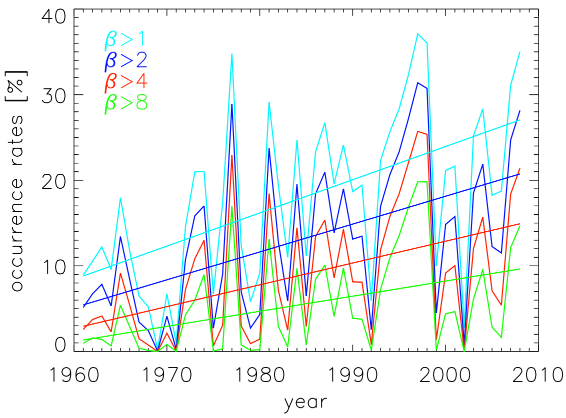

Figure 9. Occurrence rate of NLC from LIMA/ice for different thresholds for backscatter coefficients (see inlet).

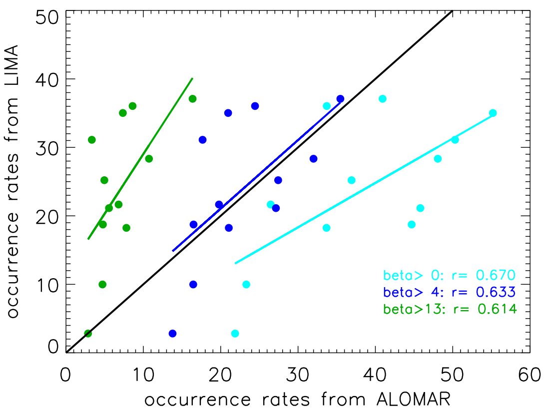

Figure 8. NLC occurrence rates at 69°N from LIMA/ice and from lidar observations. For the latter different thresholds for backscatter coefficients β have been applied (see inlet). The black line indicates a 1:1 relation.

curs with the period of strong PMCs observed by SBUV in the mid 1990s. As mentioned before the reason for this is the coincidence of low temperatures and low solar activity.

There is a tendency to a general anti-correlation between occurrence rates and Ly_α in Figure 6. A closer study shows, however, that the situation is more complex. For example, occurrence rates of strong NLC decrease from 2004 to 2007 (when Ly_α also decreases) but increase in 2008 (when Ly_α is still decreasing). The occurrence rates for $\beta > 0$ increases since 2005 when Ly_α is decreasing, in agreement with the expected anti-correlation between occurrence rates and solar activity. But at least part of this increase is presumably due to instrumental effects, more precisely to an improvement of the sensitivity to detect PMC. Occurrence rates for β >4 (long term threshold) also show a rather complex behavior.

We have investigated the correlation between occurrence rates and Ly_α in LIMA using the entire data set from 1961 to 2008. As is demonstrated in Figure 7 there is only a weak and not significant anti-correlation (r=-0.34). We note that in the current version of LIMA there is no feed-back between temperatures and Ly_α. Temperatures therefore do not vary with solar activity. Model simulations indeed show a rather small impact of Ly_α on polar summer mesosphere temperatures [16]. H_2O in LIMA partly varies with Ly_α which leaves an impact on ice layers. The correlation between water vapor (in July) and Ly_α is r=–0.54 (see LBB09). Since ice layer parameters do not only depend on H_2O but also on temperatures, the overall correlation with Ly_α is even smaller (see Figure 7). It is therefore not surprising that occurrence rates observed by the RMR-lidar at ALOMAR do not exhibit a close anti-correlation to Ly_α. However, we expect a correlation between LIMA and lidar observations. As can be seen in Figure 8 there is indeed a significant correlation between LIMA and lidar occurrence rates. The correlation coefficient is approximately r$\sim$0.65 and does not vary much with β-threshold.

The results from ALOMAR triggered a more detailed comparison with LIMA/ice. Do trends and solar cycle variations depend on β-threshold ? If yes, can this explain the decrease of occurrence rates for $\beta > 4$ observed by ALOMAR in the period 2004–2006 ? In Figure 9 we show long term variations of occurrence rates from LIMA/ice for various β-thresholds. Note that the β-values from LIMA/ice and ALOMAR cannot directly be compared since, for example, some instrumental effects are not yet taken into account in LIMA. As can be seen from Figure 9 PMC are very frequent and persistent in the mid 1990s. This has been explained earlier (see above). As expected the occurrence rate decreases if the β-threshold increases. But the relative variation from year to year does not depend on β, at least not on a first glance. This is also true for the period of lidar measurements (1997–2008).

In Figure 10 we show a detailed comparison of LIMA with the ALOMAR lidar. Indeed, LIMA and lidar observations show several common features. For example, in

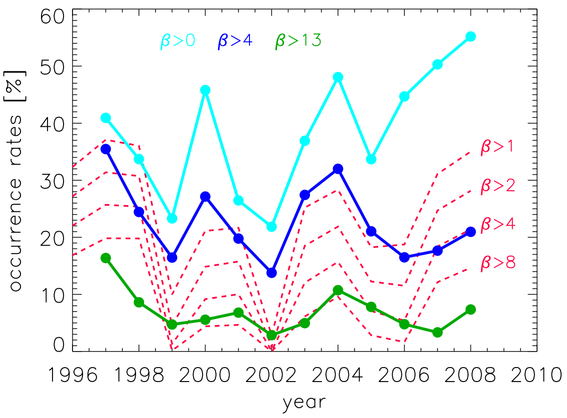

Figure 10. Occurrence rate of NLC from LIMA/ice for various β-thresholds (red dashed curves) and comparison with occurrence rates measured by the RMR lidar at ALOMAR for different β-thresholds (see inlet).

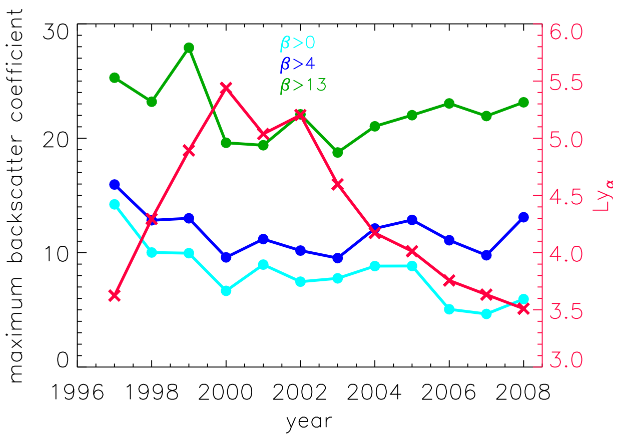

Figure 11. Same as Figure 6 but for backscatter coefficients.

the year 2002 there is a pronounced minimum in occurrence rates caused by increased planetary wave activity in the southern hemisphere [3, 13]. Furthermore, lidar occurrence rates decrease in the first 3 years of observations, in agreement with LIMA. LIMA predicts a pronounced increase of occurrence rates from 2006 to 2008. This is observed in all NLC ($\beta > 0$, presumably affected by instrumental effects) and to a lesser extent also for $\beta > 4$, but not so for strong NLC ($\beta > 13$). Note that LIMA occurrence rates decrease from 2004 to 2005 (independent of β-threshold) in nice agreement with lidar data. This decrease is caused by increasing temperatures (see Figure 2 and also Figure 4 in LBB09) which overwhelms the effect of decreasing solar activity. This example demonstrates the mutual influence of water vapor and temperatures on the occurrence of ice layers.

A closer inspection of Figure 10 shows that for certain years the relative variation of year-to-year occurrence rates for LIMA can indeed depend on the β-threshold. For example, from 2005 to 2006 occurrence rates increase for $\beta > 1$ whereas they decrease for other thresholds.

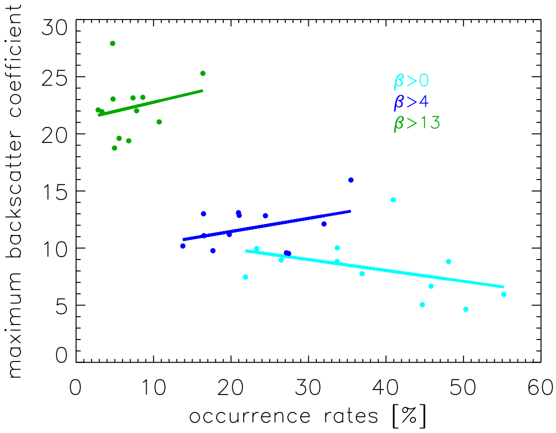

Figure 12. Maximum brightness versus occurrence for lidar observations of NLC at ALOMAR (69°N) for β-thresholds given in the inlet.

This may give a hint to explain the remaining differences between LIMA and lidar observations.

We have studied the ‘tendency’ of occurrence rates, more precisely whether occurrence rates increase or decrease from one year to the next. There is very good agreement in this parameter between LIMA and lidar observations. For example, for $\beta > 4$ there is only one year (from 2000 to 2001) where the tendencies do not agree (occurrence rates decrease in LIMA but increase in lidar data). In all other years (10 out of 11) the tendency is the same for LIMA and lidar data. This result is basically independent on the particular choice of the β-threshold for LIMA or for lidar observations. This study implies that it is ‘only’ the magnitude of occurrence rates which differs between LIMA and lidar.

4.2. Backscatter coefficients

In Figure 11 we show an update of Figure 4c of Fiedler et al. [9] regarding maximum backscatter coefficients β. In each time window of 14 minutes where a NLC was detected the maximum backscatter coefficient is determined, independent of altitude. For thresholds of $\beta >$0, >4, and >13 these β_{max}-values are averaged for each year. Since the distribution of β_{max}-values is highly skewed (concentrates on low values) the mean value is a poor representation of the average NLC brightness. Considering all NLC ($\beta >$0) there is a general trend toward lower brightness which is at least partly caused by instrumental effects: an improvement of the lidar leads to a detection of more weak which in turn decreases the mean brightness.

In our LIMA/ice simulations we observe a strong correlation between occurrence rates and maximum brightness (see Figure 11 in LBB09). Comparing Figures 6 and 11 demonstrates that this is not always the case for the lidar observations at ALOMAR. For example, for $\beta > 4$ occurrence rates decrease from 2004 to 2005 whereas

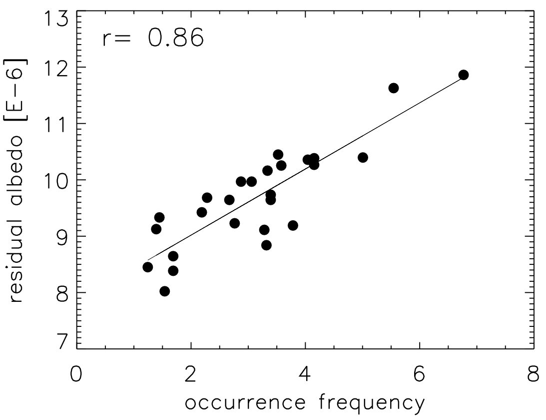

Figure 13. SBUV measurements of PMC in a latitude band 64-74°N: average albedo versus frequency of occurrence (from DeLand et al., 2007, and Shettle et al., 2009).

brightness increases in the same period. To investigate this subject further we show in Figure 12 the correlations between occurrence rates and brightness from the ALOMAR lidar. We derive correlation coefficients of r=–0.4, +0.4, and +0.23 for β >0, >4, and >13, respectively. None of the correlations is highly significant. The fact that the correlation coefficient is even negative for β >0 is tentatively explained by the increased sensitivity of the lidar caused by instrumental improvements. This allows to observe more weak clouds and supports our earlier suggestion that the increase of occurrence rates observed after 2005 is at least partly caused by instrumental effects. The correlation for the long term threshold and strong clouds (β >4, >13) is positive, but only marginally.

We have applied the same analysis for the albedo values and occurrence frequencies of SBUV PMC published by DeLand et al. [8] and Shettle et al. [17], respectively. Using data from the 64-74°N latitude band we arrive at a strong positive correlation with a correlation coefficient of r=0.86 (see Figure 13). This is in nice agreement with LIMA/ice.

4.3. Altitudes

In Figure 14 we show long term variations of NLC altitudes derived from the ALOMAR lidar. The variation of mean altitudes is very small. Independent of β threshold the peak-to-peak variation of mean altitudes is less than one kilometer. The variance is even smaller, namely σ=76 m, 86 m, and 87 m for β >0, >4, and >13, respectively. A variation of NLC altitudes with Ly_α (if any) does not exceed natural variability. This is in agreement with LIMA/ice results (see LBB09).

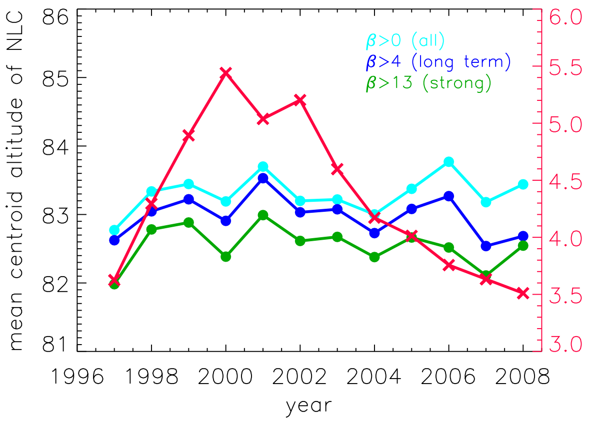

Figure 14. Same as Figure 6 but for NLC altitudes.

5. DISCUSSION AND OUTLOOK

We have analyzed 48 years of LIMA/ice modeling of ice clouds in the polar summer mesosphere. LIMA/ice adapts to the real world in the troposphere/lower stratosphere by nudging to ECMWF which is based on observations. This procedure introduces year-to-year variability and long term variations caused by trends and solar cycle. All physical processes which lead to changes in the troposphere and lower thermosphere are thereby indirectly included in LIMA/ice. This concerns, for example, dynamical influences. As was demonstrated recently planetary wave activity in the winter hemisphere may influence the summer mesopause region (and ice layers) by interhemispheric coupling. A prominent case is the year 2002 where large planetary wave activity occurred in the southern hemisphere which led to a small but significant warming around the summer mesopause and subsequently in less frequent ice layers [3, 12]. In the meantime this coupling mechanism is confirmed by GCM modeling and comparison with satellite observations [13]. Indeed, LIMA/ice arrives at low ice layer occurrence rates and brightness in 2002 (see Figure 10). This demonstrates that stratospheric effects in LIMA/ice indirectly influence mesospheric ice layers. A more direct example is given by the year 1975/76 where stratospheric temperatures are biased which directly leads to effects in mesosphere temperatures and ice layers.

LIMA detects small temperature trends at PMC altitudes (83 km) of ~0.5-1.0 K/decade, depending on latitude. These trends are caused by a shrinking of the stratosphere and by dynamical effects. Although the temperature variation is small (2-3 Kelvin) it has a significant impact on brightness and occurrence rates of PMC (less so on altitudes). Long term trends of ice layer parameters from LIMA/ice are consistent with observations from satellites and, to a certain extent, also from lidars.

We have performed a detailed comparison of LIMC/ice and lidar observations of NLC performed at ALOMAR from 1997 to 2008. We mainly obtain consistencies but also some discrepancies. There is no significant correlation of occurrence rates and Ly_α, neither in LIMA/ice nor in lidar NLC. In LIMA solar activity influences H_2O but not temperatures. Since both temperatures and water vapor determine NLC occurrence rates we do not expect a simple correlation to Ly_α in LIMA. For example, the decline of occurrence rates from 2004 to 2005 is caused by increasing temperatures, whereas water vapor increases because Ly_α decreases. From LIMA/ice we expect a strong increase of occurrence rates from 2006 to 2008, but only a moderate increase is observed. We note that SBUV indeed observes an increase. Occurrence rates in LIMA generally do not depend on the β-threshold applied, but we also found some exceptions. Regarding NLC altitudes, both LIMA and lidar observations show very little long term variation.

In the future we will elaborate further on a comparison between LIMA and observations, both from lidar and satellites. Regarding the NLC data set from ALOMAR we will investigate the potential influence of sampling and instrumental effects on the NLC statistics. We note that our LIMA is based on zonal mean quantities. It remains to be seen if longitudinal effects play a role. We also plan to consider in LIMA/ice the differences in the experimental setup for different observations, e. g. regarding scattering angle, wavelength, sampling issues, sensitivity etc. Furthermore, we will introduce greenhouse gas trends, which presumably will mainly effect the mesosphere and leave the mesopause region unchanged.

In summary, LIMA/ice demonstrates that ice layers are indeed sensitive to long term variations of background conditions. As we have shown the main changes in ice layers observed so far most likely come from the stratosphere.

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