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Long term variations in the frequency of polar mesospheric clouds in the Northern Hemisphere from SBUV

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[1] Earlier studies have indicated that there is a secular increase in the occurrence frequency of polar mesospheric clouds (PMC), along with an anti-correlation with the solar activity. The combined data records from the Solar Backscatter Ultraviolet (SBUV and SBUV/2) instruments provide the longest satellite record (28 years) of the PMC frequency of occurrence. This record has been analyzed to determine the long-term variation in the PMC occurrence frequency in each of three latitude bands (54°–64°N, 64°–74°N, 74°–82°N). This analysis includes an adjustment for changes in the local time of measurement due to the satellite orbital drift, to take into account diurnal variations in the PMC frequency. Multiple linear regression fits using solar activity and time show that the occurrence frequency nearly doubles from solar maximum to solar minimum in all latitude bands. There is a long-term increase in the occurrence frequency ranging from 7% per decade at 64°–74°N to 20% per decade at 74°–82°N. These secular increases are significant at the 95% level for the 74°–82°N and all latitudes combined. We find a time lag of half a year (with an uncertainty of one year) between the minimum solar activity and the maximum PMC activity, consistent with our previous findings for PMC albedo. **Citation:** Shettle, E. P., M. T. DeLand, G. E. Thomas, and J. J. Olivero (2009), Long term variations in the frequency of polar mesospheric clouds in the Northern Hemisphere from SBUV, *Geophys. Res. Lett.*, *36*, L02803, doi:10.1029/2008GL036048.

1. Introduction

[2] Observations of noctilucent clouds (NLC) at high summertime latitudes have been conducted since the 1880's. The term Polar Mesospheric Clouds (PMC) has generally been used for satellite observations (reviewed by *DeLand et al.* [2006]), and we will follow this nomenclature of using NLC for the ground observations and PMC for the satellite observations. Because of the sensitivity of ice properties to atmospheric forcing (e.g., temperature), long-term trends in PMC have been advocated as a means to assess global change in the mesosphere [*Thomas*, 2003]. Now that accurate satellite data are available for nearly three solar cycles, we can address the problem of PMC trends with greater statistical certainty. Our previous studies showed that average cloud albedo (brightness) have varied significantly from 1979–2006 [*DeLand et al.*, 2007]. In the present study we focus on trends in PMC frequency of occurrence (FO).

[3] An earlier analysis of variations in the PMC FO as observed by the SBUV instruments [*DeLand et al.*, 2003] found an anti-correlation with the solar activity and a weak secular increase (which was not statistically significant) for high latitudes (50–82°) in each hemisphere. In an analysis of the SAGE II PMC observations *Shettle et al.* [2002a] found an anti-correlation with the solar activity and a secular trend in the brighter PMCs, both of which were statistically significant in the NH. More recently *Kirkwood et al.* [2008], in a study of 43 years of NLC observations from the UK and Denmark found an anti-correlation of FO with the solar activity and a statistically significant secular increase when considering all NLC observations. When they excluded the faint and very faint NLCs, the secular increase was positive but no longer statistically significant.

[4] The current work uses a new SBUV PMC retrieval and analysis that applies an adjustment for local time variations in the SBUV observations. This analysis, the merging of the measurements from the different SBUV instruments, and the fit of the time trends are described in section 2. The resulting fit to the long-term variations in PMC frequency are discussed in section 3 along with a comparison with earlier results.

2. Analysis

[5] For the present analysis we use the version 3 PMC product derived from multiple SBUV instruments. This data-set was described by *DeLand et al.* [2007], and used by them to examine the long-term variations in the PMC UV albedo in both hemispheres. The most significant modification in the new PMC detection algorithm was an elimination of a bias towards increased detection of PMCs in the high solar zenith angle data. Here we will look at the long-term variations in the seasonal PMC FO, as measured by the total number of PMC detected by each of the different SBUV instruments divided by the total number of measurements from those instruments for each PMC season (30 days prior to summer solstice through 70 days after summer solstice). We examine the hemispheric average FO of all data over the 54°–82° latitude range as well as three latitude bands (54°–64°, 64°–74°, 74°–82°) within this range.

[6] Lidar measurements have shown that the FO exhibits diurnal variations [e.g., *Fiedler et al.*, 2005]. The SBUV instruments were launched into Sun-synchronous orbits with different equator crossing times, which slowly changed due to orbit drift over the life of each satellite platform. This meant that the local time of the PMC measurements changed depending on the satellite and the year [see *DeLand et al.*, 2007, Figure 2]. If not properly accounted for, diurnal variations would potentially affect the derivation of any long-term variations in the PMC FO. Direct analysis of

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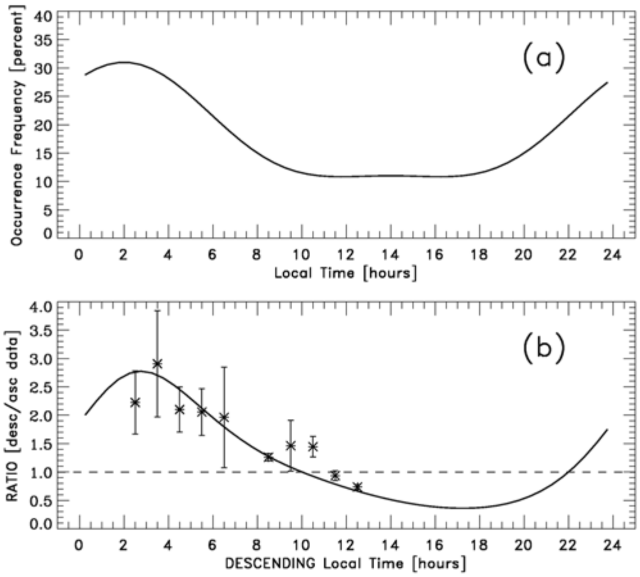

Figure 1. Local time adjustment function w used to combine SBUV Northern Hemisphere seasonally averaged PMC occurrence frequency values for long-term trend analysis. (a) Specified harmonic function with diurnal and semi-diurnal components. (b) Solid line = Ratio of harmonic function to the same function shifted by +8 hours. Asterisks = Ratio of seasonally averaged SBUV PMC occurrence frequency (descending node/ascending node) for measurements at 64°–74°N in 1-hour local time bins, following *DeLand et al.* [2007]. Error bars are the standard deviation for each bin.

local time effects on PMC albedo and FO is not practical with SBUV data, because combining many different seasons to adequately sample local time would also introduce complex inter-annual and solar cycle variations. *DeLand et al.* [2007] used the ratio of descending node and ascending node data averaged over 64°–74° latitude within each season to characterize local time variations in albedo. However, the functions derived in that paper do not provide a true local time dependence, although they were applied to the data in that manner.

[7] In the current work, we now specify a local time dependence as a harmonic function with diurnal and semi-diurnal components, similar to that used by *Fiedler et al.* [2005] and *Shettle et al.* [2002b].

$$\mathrm{F}(t) = A_0 + A_{12}{*}\cos((2{*}\pi/12){*}(t-\varphi_{12})) + A_{24}{*}\cos((2{*}\pi/24){*}(t-\varphi_{24})) \quad (1)$$

For a chosen set of coefficients, we created a time-shifted ratio curve (e.g., F(t)/F(t + 8 hr)) corresponding to the data used by *DeLand et al.* [2007, Figure 4a]. We then varied the harmonic function coefficients to get good agreement between the ratio curve and the SBUV data. Figure 1a shows the harmonic function chosen for NH FO, with the coefficients A_0 = 18.0, A_{12} = 3.0, A_{24} = 10.0, φ_{12} = 2.0, φ_{24} = 2.0, and Figure 1b shows the comparison of the ratio curve produced from this function with the SBUV data.

[8] The limited range of SBUV seasonally averaged descending node local times (approximately 2–13 hr LT), and the need to use either FO or albedo ratio values, prevents us from creating a well constrained local time adjustment function. Although various harmonic functions could produce a similar ratio curve to Figure 1b, we note that our specified harmonic function in Figure 1a is qualitatively similar to those derived by *Fiedler et al.* [2005]. The local time adjustment function is implemented for trend analysis by normalizing the harmonic function at 11 h LT, near its minimum value. Examination of individual instrument data between 63°–78°N in 5° latitude bands showed no evidence of a systematic latitude dependence, so we applied the local time adjustment function equally at all latitudes. Each individual PMC event is assigned a weight defined by w = 1/$\mathrm{F}_{\mathrm{norm}}(t_{\mathrm{local}})$, where t_{local} is the local observation time. These weights are then summed and divided by the total number of all measurements to determine the seasonal FO for further analysis. A similar procedure was applied to the PMC albedo data.

[9] We found that the phase and amplitude of the harmonic local time adjustment function adopted for NH albedo data were very similar to the linear function applied in *DeLand et al.* [2007]. As a result, the calculated long-term NH albedo changes of +4–5% per decade are slightly lower than our previous results, but still significantly greater than the calculated 95% confidence limit.

[10] Determining an appropriate local time adjustment function for SH measurements is more complicated. When we prescribe a function whose ratio curve follows SH FO ratio values (similar to the data of *DeLand et al.* [2007, Figure 4b]), we find that a significant fraction of the observations fall within the maximum of the local time adjustment function, as well as in regions where the weight w changes rapidly. Thus, the merging of individual satellite data sets for SH trend analysis is more sensitive to details in the local time adjustment function employed (such as the local time associated with a rapid change of the weight, w). The potential for problems is also greater for FO analysis because the value of w can have a factor of 3 (or more) variation between maximum and minimum, whereas the albedo local time function has an overall range of ~1.2. Because of these limitations, we have not yet been able to determine satisfactory local time adjustment functions for the SH FO. We therefore report only NH results in this paper.

[11] We have not been able to quantitatively validate our zonally averaged local time adjustment functions. Local time variations derived from ground-based lidar observations, such as those reported by *Fiedler et al.* [2005] are derived for a single location and typically show significant dependence on the PMC intensity range selected for analysis.

[12] The PMC measurements discussed here include data from seven SBUV and SBUV/2 instruments covering a 28-year period from November 1978 through August 2007. In many of those years there were two and occasionally three instruments making measurements, with minor inter-instrument differences in altitude, etc. To combine those measurements for a long-term trend analysis we follow *DeLand et al.* [2007] in adapting a form of the consensus approach of *Mears et al.* [2003], as discussed by *Christy and Norris* [2004], which determines a common basis for deriving combined time series. This approach fits a multiple-linear regression in time and solar activity to the data for each latitude band for the period when there were multiple satellites making measurements (1985–present). This fit

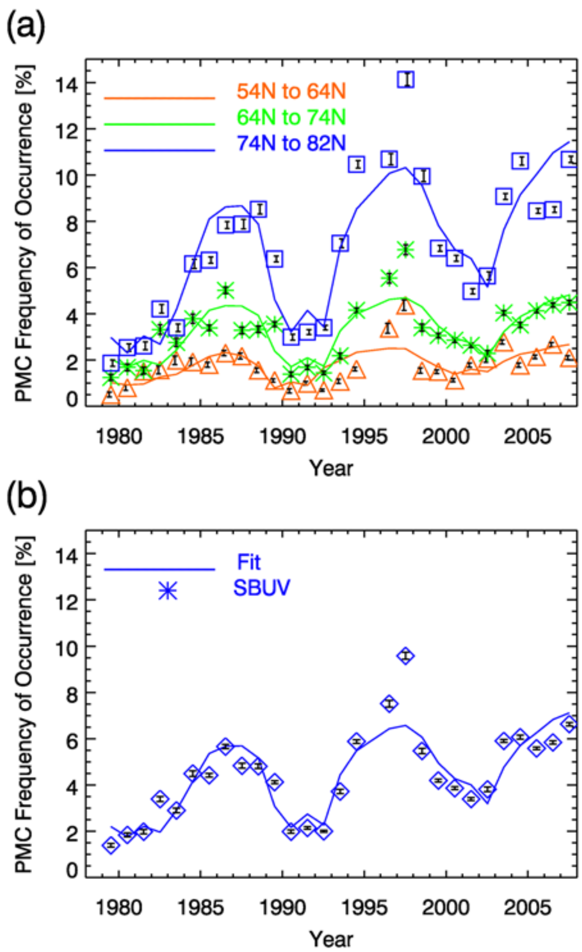

Figure 2. A comparison of the seasonal PMC frequency of occurrence measured by SBUV and the fit to a linear regression in time and solar activity (equation (1)) (a) by latitude band and (b) for all latitude bands combined between 54°N and 82°N. The error bars are the confidence limits in the individual seasonal mean values based on counting statistics, which do not reflect other factors such as inter-annual variability in large scale dynamics.

serves as a reference value using data from all of the instruments to normalize the measurements from each instrument to a common basis. The ratio of the PMC FO for each SBUV instrument averaged over the period of overlap with the reference fit is calculated, and then used to normalize that instrument's measurements to the common reference. This step produces adjustments of order ±10–20% of the seasonal FO for each instrument. For PMC seasons with multiple satellites, the normalized number of PMC detections from the different satellites were summed and divided by the total number of observations from all satellites. The result is a single FO value for each PMC season and in each latitude band.

[13] The normalized and combined PMC FO as a function of time are fit with a multiple linear regression equation in time and solar activity, as described by *DeLand et al.* [2003].

$$\mathrm{FO} = A_{\mathrm{solar}} F_{Ly\text{-}\alpha}\left(T_{\mathrm{season}} - T_{\mathrm{lag}}\right) + B_{\mathrm{trend}}\left(T_{\mathrm{season}} - 1979\right) + C \qquad (2)$$

Here $F_{Ly\text{-}\alpha}$ is the seasonally averaged solar Lyman-α flux, T_{season} is the mid-point of the PMC season, T_{lag} is the phase lag, and A_{solar}, B_{trend}, and C are fit parameters. The seasonally averaged values of the Lyman-α flux are calculated from the daily composite values developed by *Woods et al.* [2000], with updated values from the LASP Interactive Solar IRradiance Datacenter (http://lasp.colorado.edu/lisird/).

[14] The resulting fits are summarized in Table 1, and shown in Figure 2. We find an anti-correlation between the PMC FO and the solar Lyman-α flux at all latitudes, which is statistically significant at the 99% level. The amplitude of the solar cycle response is approximately a factor of two in all latitude bands, with the best statistical agreement obtained using a 0.5 year phase lag between solar flux and PMC frequency, except in the 54°–64° band where there was no apparent phase lag. With an uncertainty of ±1 year, we can not rule out zero phase lag at all latitudes. We also find a secular increase in the PMC FO at all latitudes, although the trends for the 54°–64° and 64°–74° latitude bands are not statistically significant with a greater than 10% chance that they are zero. At the highest latitude band (74°–82°) and for all latitudes combined, the secular increase is statistically significant with increases of 15% to 20% per decade.

3. Discussion

[15] The PMC FO multiple regression fit parameters listed in Table 1 for all latitudes combined agree with the results of *DeLand et al.* [2003] within their uncertainties, despite the changes in the detection algorithm and the analysis discussed above. The secular trend for all latitudes is now statistically significant because the uncertainty in the fits has been reduced by our efforts to produce an internally consistent data set, plus the six additional years of data.

[16] Our results for the lowest latitude band in the NH (54° to 64°N) can also be compared with the surface record

Table 1. Trend Fits to the PMC Frequency of Occurrence[a]

Latitude	Solar Coefficient A	Trend Coefficient B	Constant C	Lag (year)	Average (% FO)	Solar Cycle Percent Change	Long-term Percent Change per Decade	95 % Confidence per Decade	RMS Error in Fit
54°–64°N	−0.66 ± 0.16	0.017 ± 0.014	4.574	0.0	1.769	−90.0	9.9	12.4	0.60
64°–74°N	−1.26 ± 0.19	0.022 ± 0.018	8.846	0.5	3.244	−93.1	6.7	9.2	0.76
74°–82°N	−2.74 ± 0.34	0.134 ± 0.031	17.776	0.5	6.810	−96.7	19.7	9.1	1.32
54°–82°N	−1.74 ± 0.23	0.069 ± 0.021	11.626	0.5	4.406	−95.1	15.6	9.3	0.89

[a]Solar coefficient (A) = [% frequency of occurrence (FO)/(photons/cm^2/sec)]. Lyman alpha flux values divided by 10^{11} for fit calculations. Trend coefficient (B) = [% FO/year]. 'Solar Cycle' = Calculated FO change from solar minimum to solar maximum (minimum flux = 3.5×10^{11} photons/cm^2/sec, maximum flux = 6.0×10^{11} photons/cm^2/sec). 'Long-Term Change' = Calculated FO increase due to linear trend over the 28 years in the NH. '95% Confidence' = Minimum long-term FO change detectable at the 95% confidence level following *Weatherhead et al.* [1998].

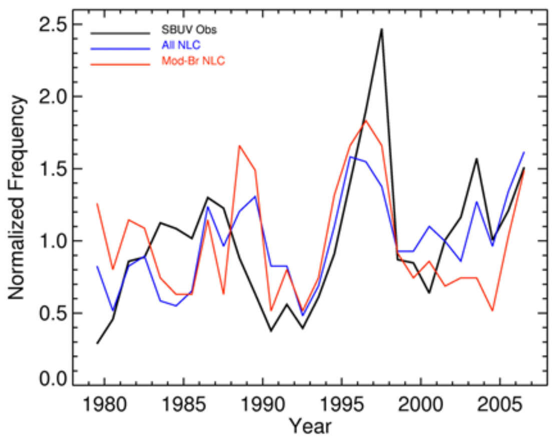

Figure 3. The normalized PMC frequencies from SBUV for 54° to 64° N (black), compared with the NLC record of *Kirkwood et al.* [2008] for all NLC (blue) and only the moderate and bright NLC (red).

of NLC reported by observers in the UK and Denmark as compiled and analyzed by *Kirkwood et al.* [2008]. These visual observations took place during 1964 through 2006, from latitudes between 50.5°N and 61°N, and longitudes between 7.5°W and 14.5°E. The NLC latitude coverage is similar to our results although they cover only 22° longitude compared with 360° for SBUV. While the SBUV latitude band is 3° north of the locations of the NLC observers, the upper edge of NLCs is typically within 5° to 25° of the northern horizon [see *Gadsden and Schröder*, 1989, Figure 3.3], which would place them 1.5° to 5.5° north of the observers. *Kirkwood et al.* [2008] fit the number of nights, N, during a summer that an NLC was reported by at least one experienced observer or two independent observations, to a linear expression in time, the 10.7 cm solar flux, and the duration of the summer in the stratosphere. They did the fits separately for all the NLC observations and just those NLC identified as "moderate" or "bright", excluding those NLC identified as "faint" or "very faint", since the increase in the latter might have been due to an "increasing skill on part of the observers in identifying faint NLC". They found a positive secular trend in N for both data sets, although it was statistically significant only in the case of all NLC. They also found an anti-correlation of N with the solar activity with a phase lag of 13 to 17 months.

[17] In Figure 3 we compare our seasonal PMC FO measurements with both data sets for N. Although our FO and the number of NLC nights per season are defined very differently, they both measure the overall cloud 'activity'. Both data sets should have at least the same character, although the numerical values are clearly different. To make the data sets as similar as possible, we normalized each data set to an average value of 1.0 over the period of SBUV measurements (1979–2006). While there is overall good agreement, there are noticeable differences in some years, especially between the SBUV frequency and N for the moderate and bright NLCs. NLC observations limited to relatively small longitude ranges may have different behavior in individual seasons compared with the zonally averaged SBUV data. The SBUV data has higher correlation coefficients with all the NLC observations (0.62) than when restricted to just the moderate and bright NLC (0.44), although both are statistically significant (at the 99% and 95% levels respectively). The 10% per decade increase in the low latitude PMCs from SBUV falls between the 4.4% per decade for the moderate and bright NLCs and 14% per decade for all NLCs in Kirkwood's analysis (we calculated the NLC trends as the relative change in the multi-year mean value for consistency with our PMC trends so they differ from those given by Kirkwood). The uncertainties on both the NLC trends and the PMC trend are all large enough that it is possible that all three are the same or the PMC trend either being smaller than the 4.4% trend of moderate to bright NC or larger than the 14% trend of all NLC.

[18] Our results for PMC frequency trends, together with those of *DeLand et al.* [2007] for cloud albedo, raise three important issues:

[19] (1) The long-term increase with latitude of cloud activity and brightness are opposite to theoretical predictions [e.g., *Siskind et al.*, 2005]. The lowest-latitude NLC region, being at the warm equatorward edge of the ice occurrence region should be the most susceptible to long-term changes in atmospheric forcings. However, SBUV is sensitive to the brightest clouds which might have a different behavior than all PMCs. We note that the both the solar response of PMC activity and the long-term trend increase dramatically with PMC brightness [e.g., *Thomas*, 2003; *Shettle et al.*, 2002b]. Thus, increasing secular trends with latitude are consistent with the well-established trend of increasing cloud brightness with latitude [*Olivero and Thomas*, 1986].

[20] (2) The NLC trends reported by *Kirkwood et al.* [2008] indicate just the opposite effect- that the inclusion of the weakest NLC in the record renders the long-term trend statistically significant. However, it is questionable that such different metrics of cloud activity should be compared to this degree of accuracy.

[21] (3) The solar-activity/PMC phase lag (0.5 year) found for the two highest latitude bins continues to appear in diverse data sets, including PMC albedo, satellite and ground-based FO. Although this quantity has the poorest confidence, its persistent occurrence among different data sets suggests it is a real effect.

4. Conclusion

[22] We have extended the earlier analysis of *DeLand et al.* [2003] of the long-term FO of polar mesospheric clouds observed by the SBUV series of satellite data to the year 2007 and now look at the trends as function of latitude. This improvement further takes into account local-time variability of PMC, so that the average FO of PMC data taken from different spacecraft (Nimbus-7 and the NOAA series of satellites) have been adjusted to a specific local time (1100 LT). We find positive secular trends at all latitudes which are statistically significant in the highest latitude band and for all latitudes combined. We have compared the SBUV trends in the lowest latitude band (54°N–64°N) with the recent NLC trend study of *Kirkwood et al.* [2008] over nearly the same latitude range, with similar results. The SBUV data has higher correlation coefficients with all the NLC observations (0.62) than when restricted to just the moderate and bright NLC (0.44), although both are statistically significant (at the 99% and 95% levels respectively).

[23] Speculation about the nature of the long-term forcing mechanisms for these trends is beyond the scope of this short note. See the review article by *DeLand et al.* [2006, and references therein] for discussion of this topic.

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