ELSEVIER
Journal of Atmospheric and Solar-Terrestrial Physics 68 (2006) 30–41
Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS
www.elsevier.com/locate/jastp

Decadal and inter-hemispheric variability in polar mesospheric clouds, water vapor, and temperature

Mark Hervig[a,*], Dave Siskind[b]

[a]GATS Inc., Driggs, Idaho 83422, USA
[b]E.O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375, USA

Available online 3 October 2005

Abstract

Variability in polar mesospheric clouds (PMCs), temperature, and water vapor over decadal time scales and also between hemispheres was examined using measurements from the Halogen Occultation Experiment (HALOE) covering 1991 to present. HALOE measurements were compared to results from a zonally averaged chemical/dynamics model (CHEM2D). HALOE indicates decadal cycles in temperature, water vapor, and PMCs that are correlated with the 11-year solar cycle. During solar cycle 23, variations in temperature and water vapor were nearly identical in the north and south. Temperatures varied by roughly 5 K at 85 km to 1 K at 30 km, with colder temperatures during solar minimum. Water vapor varied by roughly 30% at 85 km to less than 1% at 30 km, with more water vapor during solar minimum. Solar cycle variations in PMC extinction were roughly 23% in both the south and north, with brighter PMCs occurring during solar minimum. The overall picture given by HALOE is consistent with expectations, where a cooler and wetter mesosphere during solar minimum corresponds to brighter PMCs. CHEM2D confirms the solar cycle variations in temperature indicated by HALOE, but underestimates the observed solar cycle changes in H_2O. Comparing southern and northern HALOE measurements reveals warmer temperatures in the south throughout the mesosphere. CHEM2D results show the same pattern, although the model appears to overestimate the magnitude of these north-south differences. HALOE indicates that water vapor is nearly identical in the north and south, while CHEM2D predicts a wetter southern mesosphere. HALOE measurements show that northern PMCs are 30% brighter than southern clouds on average, a difference that must be related to the cooler northern summer mesosphere.

Keywords: Mesosphere; Temperature; Water vapor; PMC; Solar cycle; HALOE; Modeling

1. Introduction

Polar mesospheric clouds are observed to vary over decadal time scales and also between hemispheres (e.g., DeLand et al., 2003). Composed of water ice crystals (Hervig et al., 2001), PMCs should respond to changes in mesospheric temperature and humidity. Decadal variability in PMCs has been correlated with the 11-year solar cycle, during which solar intensity at certain wavelengths can change by a factor of two. Because water vapor is destroyed by solar lyman alpha (Ly-α) radiation and increased solar intensity enhances diabatic heating, a warmer and drier mesosphere at solar maximum should result in fewer and dimmer PMCs. Indeed, the

*Corresponding author.
E-mail address: m.e.hervig@gats-inc.com (M. Hervig).

1364-6826/$ - see front matter
doi:10.1016/j.jastp.2005.08.010

expected relationships between PMCs and the solar cycle have been observed, with PMC frequency and brightness varying over a period of roughly 10 years and exhibiting minima during solar maximum (e.g., Gadsden, 1998). While relationships between the solar cycle and upper atmospheric temperature and humidity have been documented at low to middle latitudes (e.g. Remsburg et al., 2002; Marsh et al., 2003; Chandra et al., 1997), much less information is available for high latitudes, particularly in summer. As discussed in the review by Beig et al. (2003), the existing measurements are inconsistent. One limitation is that the longest datasets are from ground based measurements of OH nightglow at 87 km which unfortunately are not available during the summertime conditions most relevant to PMC studies. Lubken (2000) examined the solar cycle dependence of mesospheric temperature at polar latitudes using falling-sphere data. While that work suggests no solar cycle dependence in mesospheric temperature, the data used were predominantly for solar minimum conditions and thus do not offer a robust conclusion. On the other hand, theoretical calculations have long predicted a solar cycle temperature change for the summer upper mesosphere (Huang and Brasseur, 1993; Siskind et al., 2005). The relationship between solar activity and mesospheric water vapor was examined by Chandra et al. (1997) using model calculations and HALOE observations between 45°S and 45°N. Their results show a clear solar cycle effect with a factor of 2 reduction in low latitude H_2O near 80 km during solar maximum. Less is known about solar cycle effects on temperature and H_2O in the polar mesosphere, although it is reasonable to expect analogous behavior to that at lower latitudes.

Another area of uncertainty concerns hemispheric differences in PMCs. In general, fewer PMCs are observed in the southern hemisphere (SH) than in the northern hemisphere (NH) (e.g. DeLand et al., 2003; Petelina et al., 2005). A logical conclusion is that the southern mesosphere is warmer and/or drier than in the north, although this supposition has not yet been documented. Indeed, Lubken et al. (1999, 2004) have presented both temperature and wind data which suggest that the Antarctic mesosphere in January is the same as that over the Arctic in July. Again, there are inconsistencies since other wind measurements suggest a stronger meridional circulation (closely linked to the mesopause temperature minimum) during the NH summer compared with the SH (e.g., Dowdy et al., 2001). Siskind et al. (2003, 2005) have argued theoretically that one would expect a warmer SH summer and that this would be reflected in fewer and dimmer PMCs in the SH.

Finally, long-term changes in PMC characteristics are expected to result from anthropogenic climate forcing (Thomas, 1996). Substantiating this connection and documenting long-term PMC changes has been challenging due to limitations in the observations of PMCs and their environment. While compelling evidence for long-term change exists (e.g., Shettle et al., 2002), open questions concerning the drivers behind PMC formation and variability have roused debate over the interpretation of these findings (von Zahn, 2003; Thomas et al., 2003). An understanding of decadal and inter-hemispheric variability in the mesosphere is important to developing a clearer picture of long-term PMC change.

The present study explores solar cycle effects and inter-hemispheric differences in the polar mesosphere using 14 years of measurements from HALOE and simulations from the CHEM2D model (Siskind et al., 2003, 2005). Of relevance to this work, HALOE offers measurements of mesospheric temperature, H_2O, and particle extinction ($\beta(\lambda)$) at five wavelengths ($\lambda = 2.45$, 3.40, 3.46, 5.26, and 6.26 μm). The present study used a new version of HALOE data ("Vpmc") with improvements targeted at the mesosphere (McHugh et al., 2003).

2. HALOE Vpmc data

The HALOE instrument onboard the Upper Atmosphere Research Satellite (UARS) has conducted solar occultation measurements from late 1991 to present. The current public HALOE data release (V19) suffers from limitations under PMC conditions, the most notable being PMC contamination in the radiometer retrievals (temperature, O_3, and H_2O). McHugh et al. (2003) described a new version of HALOE data ("Vpmc") with improvements targeted at the mesosphere including (1) the removal of PMC contamination, (2) the addition of particle measurements at 6.26 μm, (3) the reduction of vertical signal smoothing to increase resolution, and (4) raising the upper altitude limit of temperature retrievals from 78.5 to 85.5 km. Above 85.5 km temperature profiles are merged with temperatures from the MSIS-2000 model, however, this work reports only temperatures that are purely retrieved. Water vapor retrievals cease above ~87 km where the signal decreases below the measurement noise. This work reports PMC extinctions measured at 3.40 μm wavelength, $\beta(3.40)$, and PMCs were identified using the threshold approach described by Hervig et al. (2003).

The dominant errors in H_2O and temperature near PMC altitudes are likely related to the removal of PMC contamination. These errors are not inherently systematic as it is equally probable that PMC contamination is overestimated or underestimated. McHugh et al. (2003) estimate Vpmc errors in the 80–85 km region on the order of 18% for H_2O mixing ratio, 4 K for temperature, and 8% for $\beta(3.40)$. They compared HALOE V19 and Vpmc temperatures with falling sphere temperatures from a climatology reported by Lubken (1999). Note that while McHugh et al. showed HALOE temperatures at altitudes above 85.5 km, these values are not retrieved but rather based on a combination of HALOE and MSIS temperatures. Here we report only purely retrieved HALOE temperatures. The comparison of V19 and Vpmc (Fig. 4 in McHugh et al.) suggests that residual errors exist in Vpmc temperatures from 80 to 85 km. The Vpmc—falling sphere comparison shows excellent agreement at altitudes below 80 km, however, Vpmc temperatures are from 1 to 9 K warmer than the falling sphere climatology at altitudes between 80 and 85 km.

Because the PMC corrections are a dominant error source in temperature and water vapor data above 80 km, we further examine the effects of PMC contamination here. HALOE measurement averages using all available profiles ("all data") were compared to averages where all profiles known to contain PMCs were omitted ("no-PMC"). The average profiles were constructed in 5-day time bins for latitudes from 65–70°N. Mean differences for temperature and H_2O were determined using all average profiles from 10 days before to 40 days after solstice during 1992–2004 (see Fig. 1). Differences exist at all altitudes because profiles containing PMCs were omitted entirely from the "no-PMC" averages, not just at PMC altitudes. Results from this exercise should indicate the effect of residual PMC contamination in the HALOE data, but could also be affected by real geophysical variability. By excluding PMC measurements it is likely that a unique set of conditions (i.e., cold temperatures) were eliminated from the "no-PMC" averages. The "no-PMC" temperatures are about 2 ± 2 K warmer than the "all data" averages near 82 km, with smaller differences at lower and higher altitudes. This suggests that residual effects of PMC contamination are localized to altitudes between 79 and 84 km. However, the increase in temperatures for the "no-PMC" case could be a result of PMC measurements actually being colder than cases without PMCs. Water vapor changes little below 80 km in the "no-PMC" cases, with differences and difference standard deviations increasing to roughly $8\% \pm 10\%$ above 80 km. If the effects of PMC

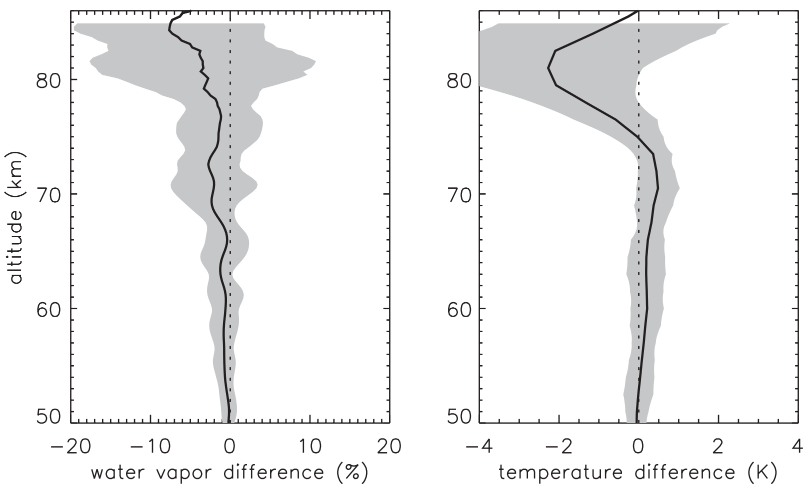

Fig. 1. The mean difference between HALOE Vpmc averages using all profiles, and averages with profiles known to contain PMCs excluded. Differences are based on average profiles constructed for 5-day time bins and latitudes from 65° to 70°N. Differences shown are averages for data from 10 days before to 40 days after solstice during 1992–2004. The difference standard deviations are indicated as shaded areas. Differences were computed as the averages of all data minus the averages with PMCs excluded.

contamination are truly separated in the "all data" versus "no-PMC" comparisons in Fig. 1, then these results suggest the magnitude of residual errors due to the PMC corrections. In the case of H_2O, the residuals are less than the 18% errors reported by McHugh et al. (2003) for the 80–85 km region. Likewise, temperature residuals (<2 K) are smaller than the reported 4 K uncertainties for 80–85 km. If these residuals are a true indication of errors related to the PMC corrections, then the PMC corrections cannot be entirely to blame for differences between Vpmc and the falling sphere climatology (Lubken, 1999) of up to 9 K above 80 km. This suggests that remaining errors in HALOE Vpmc temperatures are possibly due to other error sources, and not entirely due to the PMC corrections. Other possible error mechanisms have not been identified at this time. However, the analyses presented below were carried out with all profiles known to contain PMCs excluded and the results only changed slightly. Since our conclusions do not change if profiles containing PMCs are omitted, possible errors due to the PMC corrections are not considered a liability to this study.

3. Results

3.1. Statistical analysis of HALOE data

HALOE Vpmc data covering 1991–2004 in both hemispheres were used to characterize PMCs, temperature, and water vapor. Solar variability was examined using 81-day averages of Ly-α flux (121.6 nm wavelength) from the SOLAR2000 model (Tobiska et al., 2000). Ly-α prior to mid-2003 are based on measurements and values at later dates are predictions. While a direct relationship between water vapor and solar Ly-α is expected, Ly-α is considered as only a proxy for solar variability when comparing to other atmospheric variables. Because HALOE sampling covers the polar summer season at different times in each year, it is not possible to examine the same latitude and time in each year of the HALOE record. Since temperature, H_2O, and PMC brightness exhibit dramatic seasonal cycles, it is important to examine the same part of the season in consecutive years. This issue was dealt with by fitting a seasonal cycle to the HALOE measurements for each year within a given latitude band, and then examining data from the fits corresponding to the same day in each year to form decadal time series. For this purpose HALOE measurements at 65–70° latitude (north or south) were first averaged in 5-day time bins for each year. The averaged data points versus time were then fit according to a polynomial with three or more parameters depending on the number of data points available. In years when summer's start or end were not measured, the seasonal fits were partially constrained to data points at the beginning and end of summer determined from seasonal fits to the entire 14-year HALOE record. This step simply encouraged the fits to adopt the desired shape (concave or convex) in years when summer's onset or end were not measured. This treatment did not cause the seasonal fits to depart from the summer measurements of interest and is consistent with seasonal patterns in temperature, H_2O, and PMCs reported by previous authors (e.g. Seele and Hartogh, 1999). The seasonal fits did not attempt to account for secular trends or other lower order terms, but were rather were optimized to capture seasonal dependence and provide a smooth transition through the summer months. Examples of HALOE averages and the seasonal fits to these data are shown in Fig. 2 for 1995 and 2002. These examples illustrate the variability in HALOE sampling from year to year. For example, mid-summer was sampled more frequently in 2002 than in 1995, while summer's onset and end were better sampled in 1995. The polynomial fits offer reasonable renditions of the seasonal cycles and allow the same time of year to be examined for every year in the HALOE record.

A 14-year time series of 80 km temperature, 80 km H_2O, and peak PMC extinction is shown in Fig. 3. The individual data points represent samples at 20 days from solstice taken from the seasonal fits to HALOE data for 65–70°S and 65–70°N. Results for others days within the core summer season (−10–40 days from solstice) are consistent with the results for 20 days from solstice shown here. Solar Ly-α flux data are included in Fig. 3 for comparison. The temperature data indicate decadal cycles in both hemispheres with temperatures roughly 4 K higher during solar maximum in both hemispheres, although temperatures in the south were generally 7 K warmer than in the north (Fig. 3). Water vapor measurements exhibit a decadal cycle that is anti-correlated with solar variability, showing roughly 25% more H_2O during solar minimum. Water vapor measurements at 80 km were quite similar in the northern and southern hemispheres. PMC extinction exhibits a decadal cycle that is anti-correlated

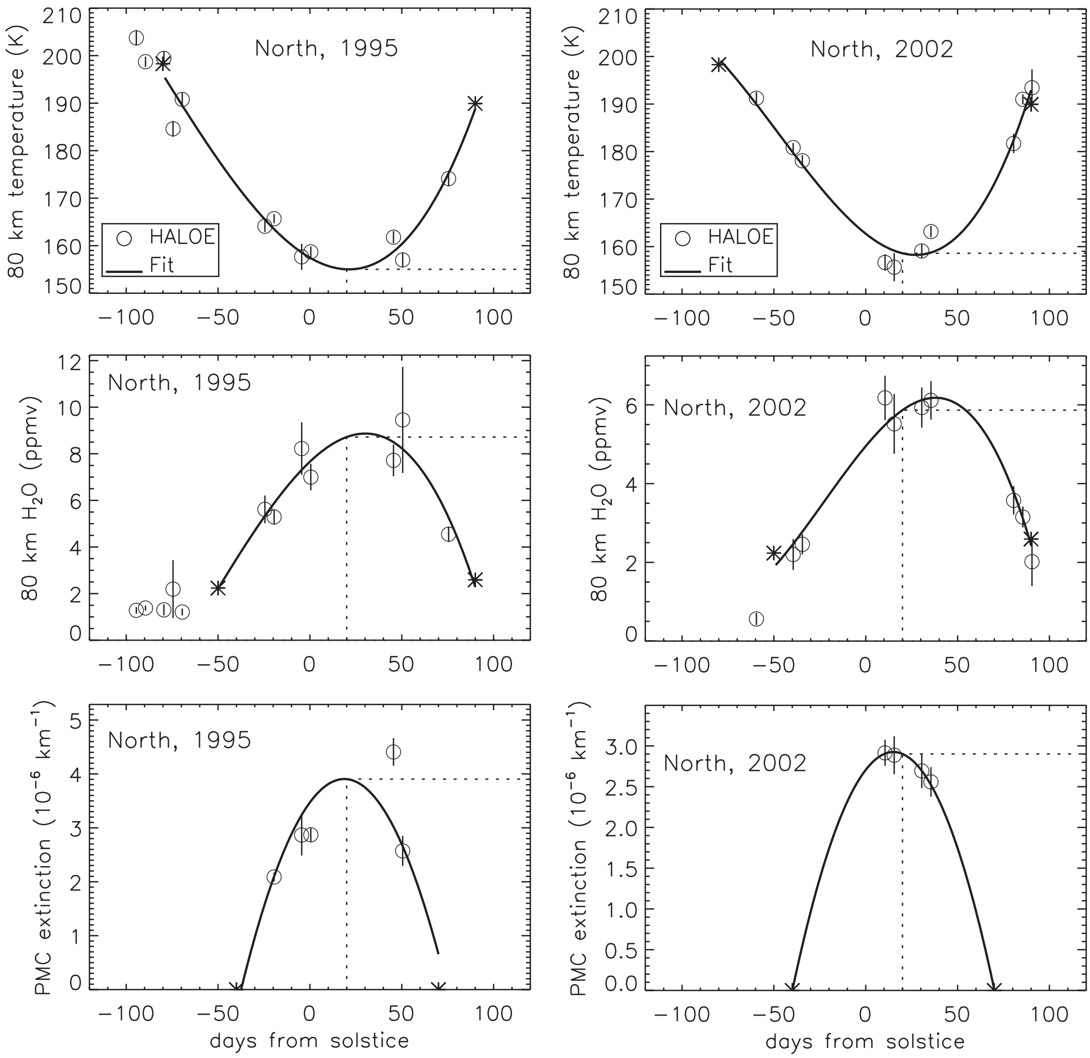

Fig. 2. Seasonal time series of 80 km temperature, 80 km H_2O, and peak PMC extinction for 1995 (left column) and 2002 (right column). HALOE points are 5-day averages for 65–70°N and polynomial fits to these data are shown. Dotted lines illustrate interpolation of the HALOE fits to 20 days from solstice in each year. Stars indicate end points inserted to direct the seasonal fits when a seasons start or end were not measured. Error bars represent the standard deviations of the means.

with solar intensity. PMC extinction in both hemispheres roughly 23% greater during solar minimum, although northern PMCs were generally 30% brighter than in the south. This hemispheric difference in PMC brightness is generally consistent with Petelina et al. (2005), who report hemispheric differences of 35–40%. The results in Fig. 3 confirm the long-standing assertion that the polar mesosphere must be warmer and drier during solar maximum, to explain observed differences in PMC activity. Fig. 3 also supports the hypothesis of Siskind et al. (2005) that a warmer SH summer would lead to weaker PMCs in the SH.

The relationships between Ly-α and temperature, H_2O, and PMC extinction were examined to determine the degree of correlation and possible time lags. Time lags between PMC brightness and solar intensity on the order of zero to two years have been reported (e.g., Gadsden, 1998; Thomas and Olivero, 2001), however, this lag is not yet understood. Correlation coefficients between Ly-α and temperature, water vapor, and PMCs were computed by performing linear regressions. The regressions were conducted for time lags from 0 to 3 years (the atmosphere follows Ly-α) in 0.2 year steps. The correlation coefficients (r) versus time lag

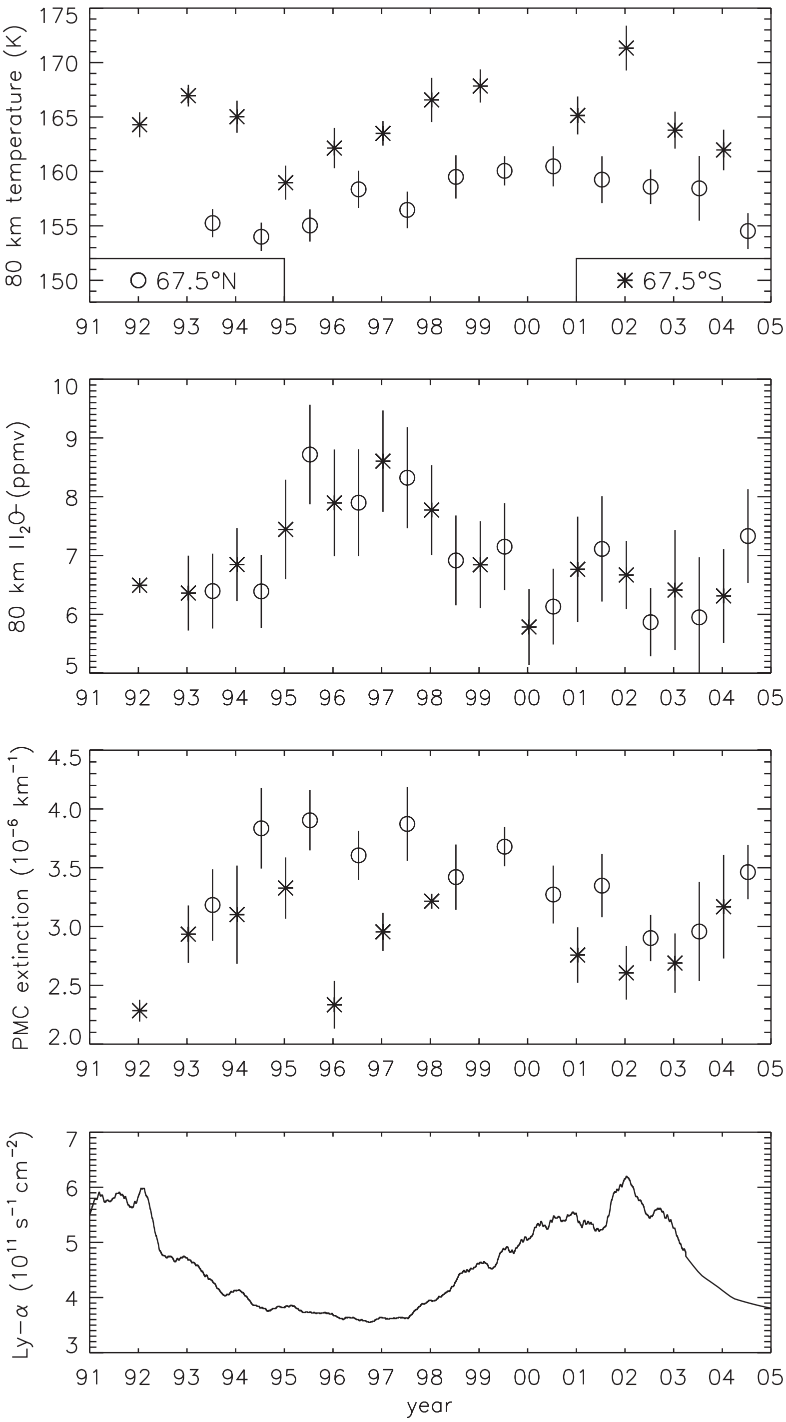

Fig. 3. Time series of 80 km temperature, 80 km H_2O, and peak 3.40 μm PMC extinction. The data points are for 20 days from solstice taken from seasonal fits to HALOE measurements at 65–70°N and 65–70°S for each year (see Fig. 2). Solar Ly-α flux data from the SOLAR2000 model. Error bars represent the standard deviations of the means.

for 80 km temperature, 80 km H_2O, and peak PMC extinctions are shown in Fig. 4. For the number of data points used in the regressions, the correlations are 95% confident when $|r|>0.6$. The probable range in time lags as indicated in Fig. 4 were estimated as the period where $|r|$ was greater than

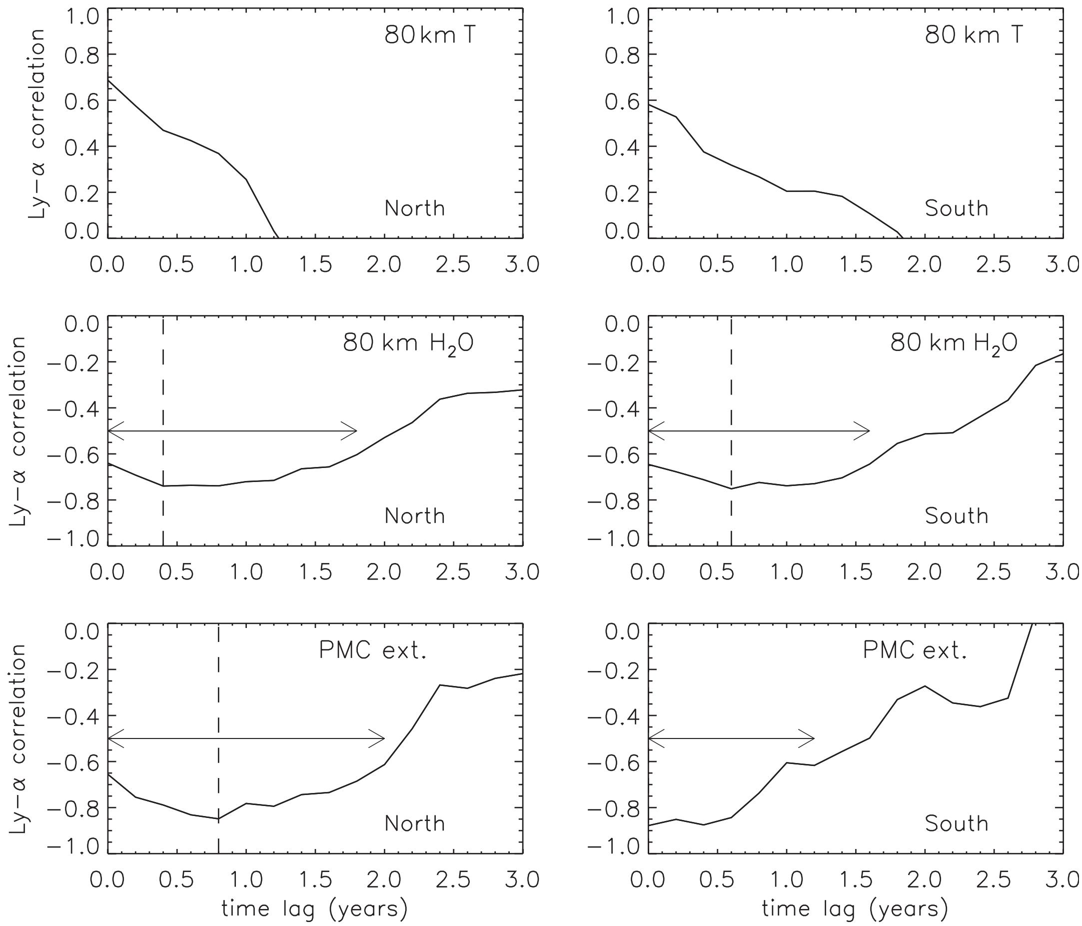

Fig. 4. The correlation coefficient versus time lag for linear regressions between solar Lyman alpha and HALOE 80 km temperature, 80 km H_2O, and peak PMC extinction. Results for the northern (left) and southern (right) hemispheres are shown. Vertical dashed lines indicate the time lag giving the best correlation. Absence of a vertical dashed line indicates that the best time lag was zero. Horizontal arrows indicate the time range where the correlation was better than the 95% confidence level ($|r|>0.6$). In the case of temperature the correlation was significant only for a lag of zero.

0.6. HALOE indicates the expected instantaneous response of temperature to changes in solar Ly-α in both the NH and SH, with r decreasing rapidly for time lags greater than zero in both hemispheres. Water vapor in the north is most strongly anti-correlated to Ly-α for time a time lag of 0.4 years, although the anti-correlation was significant for time lags from 0 to 1.8 years. Southern water vapor was similar, with the best anti-correlation for a time lag of 0.6 years and significant anti-correlations for 0 to 1.6 years. PMC extinction in the NH showed significant anti-correlation to Ly-α for time lags from 0 to 2 years with the best anti-correlation for a lag of 0.8 years. Analysis of southern PMCs suggests significant anti-correlation for time lags from 0 to 1.2 years. While the best Ly-α anti-correlation for SH PMCs was with no time lag, this result is not significant as r varies little for lags from 0 to 0.6 years. Note that the anomalously low PMC extinction for the southern summer of 1995–1996 (Fig. 3) was omitted from the Ly-α correlation analysis. In general, relationships between Ly-α and temperature, H_2O, and PMCs were remarkably similar in both hemispheres. The lag in PMC response to solar Ly-α for northern and southern HALOE PMC measurements is roughly consistent with, but slightly less than, previous reports. Assuming the PMC—Ly-α time lag is indeed real, it would seem more likely connected to water vapor which exhibits a possible time lag, while temperature responds instantaneously to Ly-α changes.

Scatter plots of Ly-α and 80 km temperature, 80 km H_2O, and peak PMC extinction are shown in Fig. 5 along with the associated linear fits. These fits

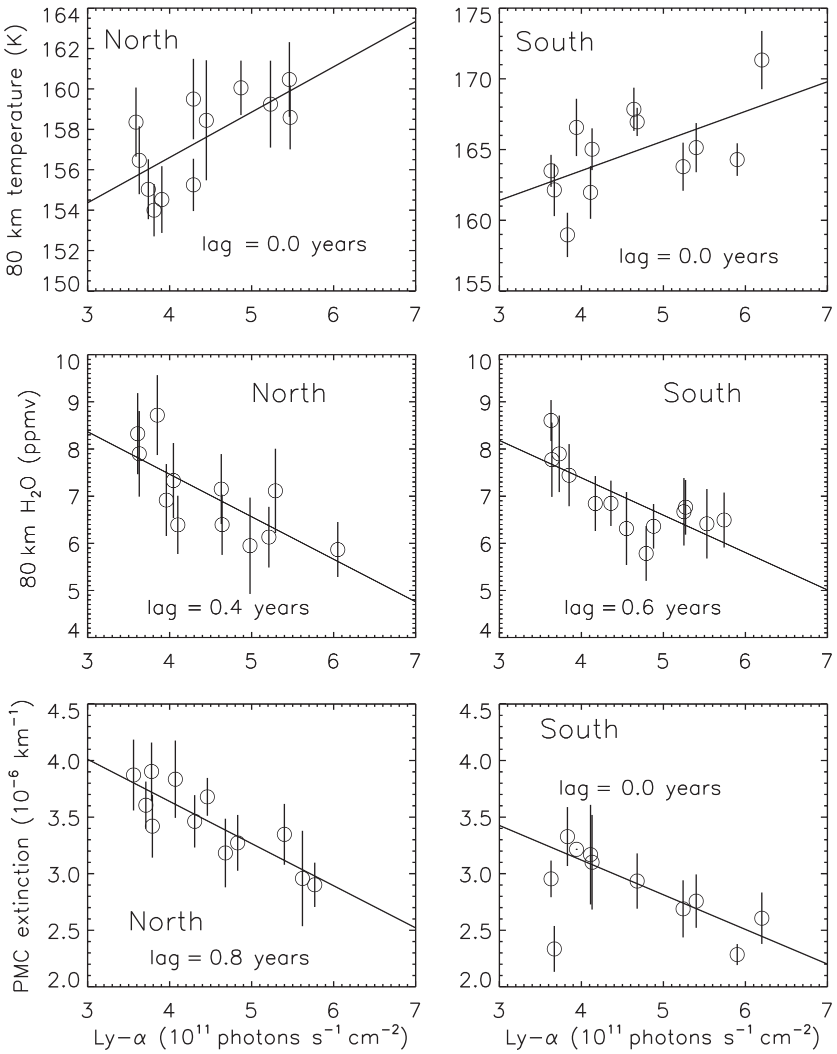

Fig. 5. Solar Lyman alpha versus HALOE 80 km temperature, 80 km H_2O, and peak PMC extinction. Linear regressions to these data considering the best time lags (as indicated) are overlain (see Table 1 for the fit parameters). The HALOE data points were taken from seasonal fits to averages for 65–70°N (left column) and 65–70°S (right column) on 20 days from solstice during each year from 1991–2004. Ly-α data are 81-day averages interpolated to HALOE times. Error bars represent the standard deviations of the means.

were performed for the best time lags (see Fig. 4), and show expected relationships between solar variability and mesospheric temperature, H_2O, and clouds. The fit parameters for the linear regressions shown in Fig. 5 are given in Table 1, along with the associated time lags and correlation coefficients. These results highlight the similarities between hemispheres in terms of the sensitivity of temperature, H_2O, and PMC extinction to changes in solar Ly-α.

3.2. Solar cycle and hemispheric variability

The linear fits shown in Fig. 5 were performed versus altitude to derive the solar cycle variation in temperature and H_2O during the past 14 years. These variations were taken from the linear fits for the range in Ly-α flux from solar minimum to solar maximum (3.55–6.20×10^{11} photons $s^{-1}\,cm^{-2}$). The variation uncertainties were determined from the standard errors in the linear regressions. Solar cycle variations in temperature and H_2O are shown versus altitude in Fig. 6. These results indicate the greatest changes in the upper mesosphere, with decreasing changes towards lower altitudes. Changes in temperature and H_2O determined from HALOE were remarkably similar in the north and south at all altitudes. Solar cycle changes in temperature and H_2O were determined from the

Table 1
Parameters for the linear regressions between solar Ly-α and HALOE 80 km temperature, 80 km H_2O, and peak 3.40 μm PMC extinction[a]

Atmospheric variable	Ly-α time lag (years) min–best–max	$A \pm \sigma_A$	$B \pm \sigma_B$	Correlation coefficient
Temperature, 65–70°N	0–0–0	147.6±3.3	2.2±0.75	0.69
Temperature, 65–70°S	0–0–0	155.1±4.4	2.1±0.92	0.59
H_2O, 65–70°N	0–0.4–1.8	11.1±1.2	−0.90±0.26	−0.74
H_2O, 65–70°S	0–0.6–1.6	10.6±1.0	−0.79±0.21	−0.75
PMC ext., 65–70°N	0–0.8–2.0	5.13±0.3	−0.37±0.07	−0.85
PMC ext., 65–70°S	0–0–1.2	4.35±0.3	−0.31±0.06	−0.89

[a]Regression results considered the best time lag with Ly-α. The atmospheric variables (X) are related to Ly-α through the expression $X = A + B(\text{Ly-}\alpha)$, for Ly-$\alpha$ in 10^{11} photons $s^{-1}\,cm^{-2}$, T in K, H_2O in ppmv, and PMC extinction in $10^{-6}\,km^{-1}$.

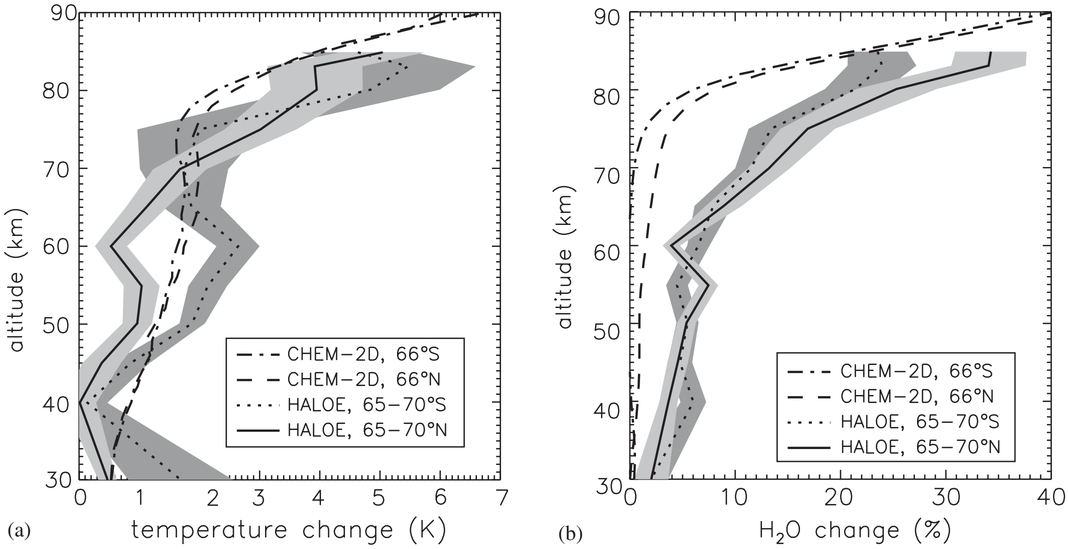

Fig. 6. Solar cycle change in (a) temperature and (b) water vapor as a function of altitude determined from HALOE measurements in the northern and southern hemispheres. The solar cycle change was determined from linear regression between HALOE data for 20 days from solstice and solar Ly-α data (as in Fig. 5). Shaded regions indicate the standard errors in the linear regressions. The solar cycle changes in temperature and H_2O determined from the CHEM2D model for 66°N and 66°S are also shown. These changes were estimated by comparing model runs for solar minimum and solar maximum conditions. Model results for 71°N and 71°S were nearly identical to those at 66°N and 66°S, respectively, and were omitted for clarity.

CHEM2D model by comparing profiles calculated for solar minimum and solar maximum conditions, at 66° and 71°N latitude and 66° and 71°S latitude (see Fig. 6). Modeled solar cycle changes in H_2O were slightly different in the south and north, although these differences may not be significant. The absolute values of temperature and water vapor for these calculations are quite similar to those shown in Siskind et al. (2005). For H_2O, the model solar cycle change is well below the observations, particularly in the 75–85 km region, although both HALOE and CHEM2D suggest a rapid increase in change above 80 km. Note that we have previously argued (Siskind et al., 2005) that our low latitude results agree well with the HALOE-based analysis of Marsh et al. (2003). If so, our relatively poor agreement here would suggest a possible process which is unique to the polar summer. One possibility is that the recycling of H_2O due to condensation and sublimation of PMC particles (Hervig et al., 2003) could vary with solar activity since it is temperature dependent. If so, this suggests that a complete model analysis of solar cycle H_2O behavior should include an interactive PMC parameterization, although even then it is hard to imagine an effect diffusing down to 60 km as suggested by the data. Von Zahn et al. (2004) examined this effect over a short period (5 days) and found only a small enhancement in the solar cycle response of H_2O in a narrow layer near the base of the PMC layer. PMC microphysics were recently included in CHEM2D (Siskind and Stevens, 2005) and this configuration will be used to examine these issues in greater detail. Comparing modeled and measured solar cycle changes in temperature shows generally good agreement up to ~75 km, above which the model falls slightly below the observations. Only results for 66°N and 66°S are shown since the model indicates identical temperature changes at 71°N and 71°S, respectively. The general increase with altitude reflects the greater variability in the wavelengths of the solar spectrum which are absorbed at higher altitudes; this is a standard feature of 2D models, but due to lack of observations has not been validated for high latitude conditions until now.

South–north differences in H_2O and temperature are shown versus altitude in Fig. 7. The HALOE differences are averages for all years from 1991 to 2004 and were calculated by subtracting a northern summer measurement from the preceding southern summer measurement, for the same day (relative to solstice) and latitude band. The differences are for 20 days from solstice taken from the seasonal fits to HALOE data (e.g., Fig. 3). South–north differences in temperature and H_2O were also determined from the CHEM2D model (Siskind et al., 2003) for both solar minimum and maximum conditions. Both HALOE and CHEM2D indicate that the southern mesosphere is warmer than the north at all altitudes, and show similar altitude dependence with the largest temperature differences occurring above 70 km (Fig. 7). This south–north temperature difference has been attributed to differential filtering of gravity waves in the summer troposphere and stratosphere (Siskind et al., 2003). While the overall qualitative agreement between model and observations is encouraging, the model overestimates the NH—SH differences above 75 km. Siskind et al. (2005) suggested that feedbacks which are missing in the model might reduce hemispheric asymmetry and improve the quantitative agreement with the observations. In addition, we point out that the model makes the crudest possible assumption about the gravity wave sources in the lower atmosphere, namely that they are equal in the northern and southern hemispheres (e.g. Siskind et al., 2003). A small change in that assumption will give different results. Given that uncertainty, the excellent qualitative agreement seen at all altitudes in the upper stratosphere and mesosphere in Fig. 7 suggest that the fundamental patterns we observe and the general theory we propose are consistent. Regarding water vapor, CHEM2D shows more water vapor in the south than in the north (Fig. 7b; see also Siskind et al., 2005). HALOE measurements, however, do

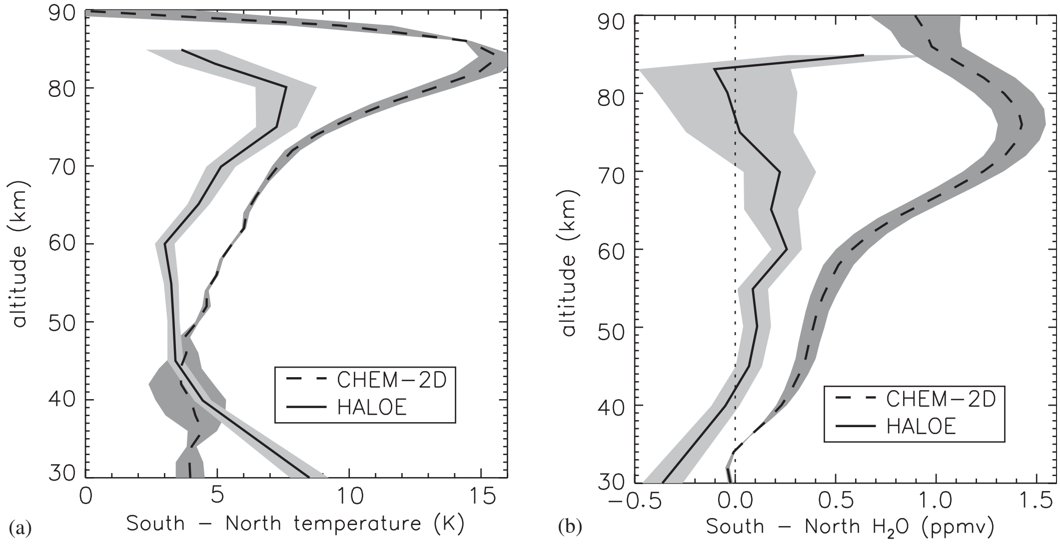

Fig. 7. Inter-hemispheric differences (south–north) in (a) temperature and (b) water vapor as a function of altitude. The HALOE results are averages for 1991–2004 and latitudes from 65°–70°. Shaded areas indicate the root sum squared of the standard deviation of the mean measurement errors, and the standard deviation of the mean SH-NH difference. The HALOE differences are compared to hemispheric differences based on model results from CHEM2D for latitudes of 66° and 71° north and south for both solar maximum and solar minimum conditions. The average CHEM2D results are shown with standard deviations indicated by shaded areas.

not support this pattern and indicate that water vapor is nearly identical in the north and south. It is unclear whether this is a true global scale discrepancy or simply the consequence of sampling the model at a single latitude which might not be representative. More data at a wider range of latitudes would help resolve this question. In any event, since the hemispheric differences in water vapor are small, temperature differences are undoubtedly the dominant cause of brighter PMCs in the north.

4. Conclusions

This work reports a new and comprehensive view of decadal and inter-hemispheric variability in polar mesospheric clouds, water vapor, and temperature. HALOE measurements during 1991–2004 indicate decadal cycles in polar mesospheric clouds, temperature, and water vapor, with expected relationships to the solar cycle. During solar minimum, northern and southern PMCs were found to be ~23% brighter than during solar maximum. This change is apparently related to solar cycle changes in temperature and water vapor, where the polar mesosphere was both colder and more humid during solar minimum. The variation in PMC extinction was observed to lag solar Lyman alpha in both hemispheres. This lag is more likely related to water vapor than temperature, since water vapor changes lagged solar activity while temperature changes did not. Both HALOE measurements and CHEM2D model results indicate warmer temperatures in the southern hemisphere at all altitudes. HALOE indicates nearly identical water vapor in the north and south, while CHEM2D suggests a wetter southern mesosphere. The fact that brighter PMCs are observed in the north is thus attributed to the colder temperatures there, consistent with recent model calculations reported by Siskind et al. (2005). The HALOE Vpmc data set offers the unique advantage of providing simultaneous water vapor, temperature, and PMC measurements. These data offer the potential to characterize our baseline understanding of polar mesospheric climate and the processes behind PMC formation and variability.

Acknowledgements

We thank Marty McHugh, Jon Wrotny, and Larry Gordley for efforts in developing the Vpmc HALOE data set, and Mike Stevens for helpful discussion and insight. This work was funded in part by NASA Office of Space Sciences grant numbers NASW-02013 to GATS Inc. and Intergovernmental transfer W-10,292 to NRL, and also by the Office of Naval Research.

References

Beig, G., et al., 2003. Review of mesospheric temperature trends. Review of Geophysics 41 (4), 1015.

Chandra, C., Jackman, C.H., Fleming, E.L., Russell III, J.M., 1997. The seasonal and long term changes in mesospheric water vapor. Geophysical Research Letters 24, 639–642.

DeLand, M.T., Shettle, E.P., Thomas, G.E., Olivero, J.J., 2003. Solar backscattered ultraviolet (SBUV) observations of polar mesospheric clouds (PMCs) over two solar cycles. Journal of Geophysical Research 108 (D8), 8445.

Dowdy, A., Vincent, R.A., Igarashi, K., Murayama, Y., Murphy, D.J., 2001. A comparison of mean winds and gravity wave activity in the northern and southern polar MLT. Geophysical Research Letters 28, 1475–1478.

Gadsden, M., 1998. The North–West Europe data on noctilucent clouds: a survey. Journal of Atmospheric and Solar-Terrestrial Physics 60, 1163–1174.

Hervig, M.E., Thompson, R.E., McHugh, M., Gordley, L.L., Russell III, J.M., Summers, M.E., 2001. First confirmation that water ice is the primary component of polar mesospheric clouds. Geophysical Research Letters 28, 971–974.

Hervig, M., McHugh, M., Summers, M., 2003. Water vapor enhancement in the polar summer mesosphere and its relationship to polar mesospheric clouds. Geophysical Research Letters 30 (20), 2041.

Huang, T.Y.W., Brasseur, G.P., 1993. Effect of long-term solar variability in a two-dimensional interactive model of the middle atmosphere. Journal of Geophysical Research 98, 20413.

Lubken, F.-J., 1999. Thermal structure of the Arctic summer mesosphere. Journal of Geophysical Research 104, 9135–9149.

Lubken, F.-J., 2000. Nearly zero temperature trend in the polar summer mesosphere. Geophysical Research Letters 27, 3603–3606.

Lubken, F.-J., Jarvis, M.J., Jones, G.O.L., 1999. First in-situ temperature measurements at the Antarctic summer mesopause. Geophysical Research Letters 24, 3581.

Lubken, F.-J., Mullemann, A., Jarvis, M.J., 2004. Temperatures and horizontal winds in the Antarctic summer mesosphere. Journal of Geophysical Research 109.

Marsh, D., Smith, A., Noble, E., 2003. Mesospheric ozone response to changes in water vapor. Journal of Geophysical Research 108 (D3), 4109.

McHugh, M., Hervig, M., Magill, B., Thompson, R.E., Remsberg, E., Wrotny, J., Russell III, J., 2003. Improved mesospheric temperature, water vapor, and polar mesospheric cloud extinctions from HALOE. Geophysical Research Letters 30.

Petelina, S.V., Llewellyn, E.J., Degenstein, D.A., Lloyd, N.D., 2005. Odin/OSIRIS limb observations of polar mesospheric clouds in 2001–2003. Journal of Atmospheric and Solar-Terrestrial Physics, this issue, doi:10.1016/j.jastp.2005.08.004.

Remsburg, E.E., Bhatt, P.P., Deaver, L.E., 2002. Seasonal and long term variations in middle atmosphere temperature from HALOE on UARS. Journal of Geophysical Research 107 (D19), 4411.

Seele, C., Hartogh, P., 1999. Water vapor of the polar middle atmosphere: annual variation and summer mesosphere conditions as observed by ground-based microwave spectroscopy. Geophysical Research Letters 26 (11), 1517–1520.

Shettle, E.P., Thomas, G.E., Olivero, J.J., Evans, W.F.J., Debrestian, D.J., Chardon, L., 2002. Three-satellite comparison of polar mesospheric clouds: evidence for long-term change. Journal of Geophysical Research 107 (D12), 4134.

Siskind, D.E., Eckermann, S.D., McCormack, J.P., Alexander, M.J., Bacmeister, J.T., 2003. Hemispheric differences in the temperature of the summertime stratosphere and mesosphere. Journal of Geophysical Research 108, 4051.

Siskind, D.E., Stevens, M.H., 2005. A radiative feedback from an interactive PMC parameterization in a two dimensional model. Advances in Space Research, in press.

Siskind, D.E., Stevens, M.H., Englert, C.R., 2005. A model study of global variability in mesospheric cloudiness. Journal of Atmospheric and Solar-Terrestrial Physics 63, 501–513.

Thomas, G.E., 1996. Is the polar mesosphere the miner's canary of global change? Advances in Space Research 18, 149–158.

Thomas, G.E., Olivero, J.J., 2001. Noctilucent clouds and possible indicators of global climate change in the mesosphere. Advances in Space Research 28, 937–946.

Thomas, G.E., Olivero, J.J., DeLand, M., Shettle, E.P., 2003. Comment on Are noctilucent clouds truly a 'miner's canary' for global change? EOS 84 (36).

Tobiska, W.K., Woods, T., Eparvier, F., Viereck, R., Floyd, L., Bouwer, D., Rottman, G., White, O.R., 2000. The SOLAR2000 empirical solar irradiance model and forecast tool. Journal of Atmospheric and Solar-Terrestrial Physics 62, 1233–1250.

von Zahn, U., 2003. Are noctilucent clouds truly a "miner's canary" for global change? EOS 84 (28).

von Zahn, U., Baumgarten, G., Berger, U., Fiedler, J., Hartogh, P., 2004. Noctilucent clouds and the mesospheric water vapour: the past decade. Atmospheric Chemistry and Physics 4, 2449–2464.