Observed seasonal to decadal-scale responses in mesospheric water vapor

Ellis Remsberg

Science Directorate, NASA Langley Research Center, Hampton, VA

E. E. Remsberg, Science Directorate, Mail Stop 401B, NASA Langley Research Center, Hampton, VA 23681-2199. (e-mail: Ellis.E.Remsberg@nasa.gov)
Abstract.
The 14-yr (1991-2005) time series of mesospheric water vapor from the Halogen Occultation Experiment (HALOE) are analyzed using multiple linear regression (MLR) techniques for their seasonal and longer-period terms from 45S to 45N. The distribution of annual average water vapor shows a decrease from a maximum of 6.5 ppmv at 0.2 hPa to about 3.2 ppmv at 0.01 hPa, in accord with the effects of the photolysis of water vapor due to the Lyman-α flux. The distribution of the semi-annual cycle amplitudes is nearly hemispherically symmetric at the low latitudes, while that of the annual cycles show larger amplitudes in the northern hemisphere. The diagnosed 11-yr, or solar cycle, max minus min, water vapor values are of the order of several percent at 0.2 hPa to about 23% at 0.01 hPa. The solar cycle terms have larger values in the northern than in the southern hemisphere, particularly in the middle mesosphere, and the associated linear trend terms are anomalously large in the same region. Those anomalies are due, at least in part, to the fact that the amplitudes of the seasonal cycles were varying at northern mid latitudes during 1991-2005, while the corresponding seasonal terms of the MLR model do not allow for that possibility. Although the 11-yr variation in water vapor is essentially hemispherically-symmetric and anti-phased with the solar cycle flux near 0.01 hPa, the concurrent temperature variations produce slightly colder conditions at the northern high latitudes at solar minimum. It is concluded that this temperature difference is most likely the reason for the greater occurrence of polar mesospheric clouds at the northern versus the southern high latitudes at solar minimum during the HALOE time period.
1. **Background and Objectives**

Water vapor (H$_2$O) in the low to middle mesosphere is determined by its so-called “entry level” value to the stratosphere from the tropical upper troposphere plus the effects of the oxidation of methane (CH$_4$) to H$_2$O in the upper stratosphere. That conversion of CH$_4$ to H$_2$O is essentially complete for air reaching the middle mesosphere. Water vapor and its component radicals also interact chemically with odd oxygen in the mesosphere. The distribution of H$_2$O in the middle and upper mesosphere is determined by the effects of global-scale, net transport processes and by photolysis from Lyman-alpha (Ly-α) radiation that is most efficient near the mesopause. The largest periodic variations of H$_2$O in the upper mesosphere are found at the higher latitudes and on both seasonal and 11-yr (or solar cycle) time scales. Thus, the observed variations of H$_2$O can be a useful diagnostic of the performance of radiative-chemical-transport models and of global change in the mesosphere [Brasseur and Solomon, 1984; Laštovička et al., 2008].

Currently, only a few multiyear datasets are available for characterizing the large-scale variations of water vapor in the mesosphere. In particular, H$_2$O profiles were obtained with a vertical resolution of about 2.5 km from cloud tops to just above the 0.01-hPa level for more than one complete solar cycle (1991-2005) by the Halogen Occultation Experiment (HALOE) of the Upper Atmosphere Research Satellite (UARS) [Russell et al., 1993; Harries et al., 1996; Kley et al., 2000]. Individual retrieved H$_2$O mixing ratio profiles appear rather noisy (or oscillatory with altitude) in the mesosphere, due to the non-linear relationship between the retrieved H$_2$O and the small changes of the observed 6.6-µm limb transmission values. Therefore, this study analyzes time series of points obtained by averaging mixing ratio profiles for each of the HALOE sunset
(SS) and sunrise (SR) orbital crossing occurrences of selected latitude zones. In order to obtain reasonable zonal mean estimates for a latitude crossing, the profiles are binned according to 20 degree-wide latitude zones. A minimum of 5 profiles is required for a bin-average, although most of the averages are derived from many more profiles. These criteria are providing time series points that are much less noisy and are representative of zonal means because the large-scale longitudinal gradients of H$_2$O are weak in the mesosphere at low and middle latitudes.

Section 2 describes briefly the multiple linear regression (MLR) model analysis approach that is used to obtain the seasonal and longer-term variations of HALOE Version 19 (V19) H$_2$O versus latitude and for pressure-altitudes from 0.2 to 0.01 hPa. It also provides the latitude versus pressure distributions of the amplitudes of the semi-annual and annual terms from the regression models. Section 3 shows results for the 11-yr or the solar cycle (SC-like) terms and relates the distribution of their “max minus min” H$_2$O values with those from model simulations reported in the literature. It also contains findings for the concurrently analyzed, linear trend terms and of the potentially confounding effects for the determination of their SC-like responses. Section 4 discusses the SC-like variations in temperature and in H$_2$O plus their relation to the occurrences of polar mesospheric clouds (PMC) near 0.01 hPa. Section 5 summarizes the findings.

2. Analysis Procedure and the Seasonal and QBO-like Variations

Remsberg [2008a, his Figure 1] showed that the time series of tangent point measurement locations for the HALOE SR and SS events of 2001, for example, are representative of each of the seasons and for both hemispheres, at least Equatorward of about 55 degrees of latitude.
Conversely, the very high latitudes were not sampled at all during winter, due to the orbital inclination of UARS and of the Earth with respect to the Sun. Mesospheric H$_2$O attains its minimum values during winter at high latitudes, which means that the amplitude of its annual cycle may be significantly underestimated from the HALOE data in those regions of the upper mesosphere. It was also noted by McHugh et al. [2003] that a PMC feature in the measurement line-of-sight can contaminate the retrieved H$_2$O profile significantly. Time series of HALOE H$_2$O data are not considered for analysis at the higher latitudes for these reasons.

The MLR analysis approach of the present study follows that given in Remsberg [2008a] and is described briefly here. Zonal, bin-averages of the V19 SS and then the SR profiles are obtained for ten, 20-degree wide latitude zones from 45S to 45N and for 9 pressure levels from 0.2 hPa (or near 60 km) to 0.01 hPa (or near 80 km). Each of the 90 time series of the set of SS plus SR H$_2$O is analyzed by MLR techniques to obtain their annual oscillation (AO) and semi-annual oscillation (SAO) terms, any weak quasi-biennial oscillation (QBO)-like and sub-biennial (interannual or IA) terms, their decadal-scale (11-yr) terms, and linear trend terms. The sub-biennial term occurs as a result of interactions between the AO and QBO terms, and it has a period of about 21 months. For a given latitude bin and pressure-altitude the amplitudes and phases of the periodic terms, including the QBO and 11-yr terms, are based on a fitting with a set of predictors that are simply harmonics of specific periods. This approach differs from the more common practice of fitting to a proxy for an underlying physical process, such as the f10.7-cm flux for the SC and a couple of tropical wind indices for the QBO term (e.g., Randel et al., 2000; Wallace et al., 1993). On the other hand, the present approach is particularly useful for
identifying interannual responses in the mesosphere and for determining whether the primary
decadal-scale response of H$_2$O is truly anti-phased with the SC uv-flux forcing.

It is easy to confound the effects of SC and trend terms for the time series, especially when
adjacent zonal mean points are correlated. Those effects are accounted for to first order by
conducting a two-step process with the MLR model in the manner of Tiao et al. [1990] and
Remsberg [2008a]. Initially, the set of relevant model terms are fit to the H$_2$O time series, and a
weak positive, lag-1 autoregression (AR1) coefficient is obtained from the time series of the
noise residuals. Then, the model terms are transformed to account for the AR1 coefficient, and
the data time series are refit to obtain the coefficients for the final MLR terms.

At this point it is noted that the 14-yr time series consist of alternating SR and SS points and that
there are slight differences between the means of the SR and SS H$_2$O values for several extended
periods of the dataset. Those differences are due to small biases from the FOV lockdown of the
HALOE instrument in its SR transmission profiles. The effect is evident as an exaggerated
vertical oscillation in the retrieved SR H$_2$O profile near 0.1 hPa—the H$_2$O values are too small
just below and too large just above that pressure level. The incorrect lockdown for those SR
scans leads to weakly negative AR1 coefficients that are accommodated by the transformed
terms of the final MLR model for the combined (SR plus SS) HALOE H$_2$O time series.
Figure 1 is an example time series of HALOE V19 H₂O at 35N and 0.015 hPa (near 75 km). The solid and open points are the bin-averaged SS and SR values, respectively, for HALOE tangent-point measurements made at 35±10N throughout the years. The oscillating curve is the MLR model fit to the points, and it is composed of constant (Const), AO, SAO, QBO (853-dy or 28 mo), IA (640-dy or 21-mo), 11-yr (or SC-like), and linear (Lin) trend terms. There is a clear annual cycle in the data at this latitude and level. The straight line in Figure 1 is just the sum of the Const and Lin terms. Figure 2 is the time series of the data minus model residuals (in ppmv) from Figure 1. No apparent periodic structure is remaining in those residuals—an important test for the acceptance of the final MLR model.

The HALOE H₂O data time series of Figure 1 exhibits a weak, near-biennial variation; the amplitude of the associated, model QBO (28-mo) term is discussed later in this section. There are also clear relative minima at about 1991 and 2002, in accord with the estimated times for the maxima of the Ly-α photolysis flux of the 11-yr solar cycle. Such a direct response is expected for the upper mesosphere. The response to Ly-α is much weaker in the middle mesosphere and is most likely mixed with the larger H₂O responses of the higher altitudes and latitudes as a result of its annually-averaged, net circulation. In order to assess the prospect of a delayed, SC-like response for the H₂O of the middle mesosphere, a simple sinusoid of 11-yr period was used to fit the data at all altitudes and latitudes. The amplitudes of the 11-yr terms were determined, but then the phases were checked to see how well the 11-yr H₂O maxima coincided with the estimated minima for a Ly-α or other solar cycle (SC) flux proxy. Findings for the 11-yr terms are presented and discussed in Section 3.
Figures 3-5 show the latitude versus pressure cross sections of (a) the constant term (in ppmv),
(b) the amplitude of the SAO term (in %), and (c) the amplitude of the AO term (in %),
respectively. Since HALOE samples a latitude zone infrequently, one must combine the
constant term, seasonal amplitudes, and their phases, in order to generate an H$_2$O distribution for
comparisons with models at a specific time of the year, for example in January. Jackson et al.
[1998] showed and discussed these terms for the mesosphere from the first 5 years of the
HALOE data, and the results of this section are compared with them briefly. Figure 3 is the
distribution of the constant terms, i.e., their 14-yr, annual average H$_2$O mixing ratios. Those
values decrease from a maximum of about 6.5 ppmv in the mid-mesosphere to 3.2 ppmv near
0.01 hPa. Estimates of total bias error for HALOE zonal mean H$_2$O are of order 10% in the
mesosphere [Harries et al., 1996]. Comparisons with other satellite data indicate that the
HALOE values may be, in fact, too low but by no more than 12% in the same altitude region
[Lambert et al., 2007; Milz et al., 2009]. The relative variations of HALOE H$_2$O with altitude
and latitude are likely more accurate because the primary systematic errors do not depend on
atmospheric state. The decreasing values of H$_2$O with altitude are due largely to the effects of
Ly-$\alpha$ photolysis. Their decrease toward higher latitudes is indicative of the descent of air at polar
winter latitudes. There is also a slight hemispheric asymmetry for the northern versus the
southern latitudes for this distribution.

Figure 4 is the distribution of the SAO amplitudes, which have their greatest percentage values
(or order 20%) near 0.01 hPa. This distribution agrees well with the observations of the Sub-
Millimetre Radiometer (SMR) instrument of the ODIN satellite [Lossow et al., 2008], even near 0.01 hPa, where the HALOE H$_2$O profiles are close to their signal-to-noise limit. The HALOE SAO amplitudes occur nearly symmetric about the Equator and with their minimum values in the subtropics. The distribution of the phases of the SAO maxima for their first cycles is shown in Table 1 (in days from January 1) and is also nearly hemispherically-symmetric. A steady descent is indicated for the SAO from the upper to the middle mesosphere at the low latitudes (15S to 15N), in accord with the SAO phase observations and forcings for other atmospheric parameters [Garcia et al., 1997]. At the middle latitudes the descent of the SAO is also apparent in the southern hemisphere, while it is variable or nearly stationary with altitude in the northern hemisphere.

Figure 5 is the distribution of the amplitudes of the annual cycle (AO) terms; amplitudes exceed 30% at the high altitudes and latitudes. The hemispheric asymmetry of this term is quite striking and is responsible for the observed hemispheric asymmetry in the annual average mixing ratios of Figure 3. Minimum amplitudes occur along a vertical axis centered near 15S, and this finding agrees very well with the SMR observations of Lossow et al. [2008, see their Figure 8]. Similar plots in Jackson et al. [1998] show that this vertical axis is nearer to 5S. On the other hand, the AO amplitudes in Figure 5 are approximately the same at 45S and 45N at the 0.2-hPa level. The generally smaller AO amplitudes of the southern hemisphere may be due, in small part, to the fact that the Earth-Sun distance is at a minimum and the associated Ly-α flux at a maximum in SH summer, which would slightly offset the tendency of the summer upwelling to increase H$_2$O. However, this circumstance cannot explain the axis of minimum amplitudes at 15S.
Table 2 shows the time of occurrence of the AO maximum in H₂O in days past January 1. Those phases are anti-symmetric between the two hemispheres (but seasonally symmetric), especially at the middle latitudes. Phase propagation is more complicated in the subtropics, however. For example, at the 0.05-hPa level the AO phase at 15N is very similar to that of northern middle latitudes, while the AO phase at 15S is one-quarter cycle out-of-phase with that at 35-45S. Clearly, the seasonal cycle in the NH versus the SH is projecting differently onto the 12-mo and 6-mo harmonics of the MLR fit, especially for the subtropics. Those two terms have significant amplitudes at 15N and 0.05 hPa as indicated in Figure 6, while the structure of the points in the corresponding time series at 15S is much weaker (not shown). Most likely the characters of both the AO and the SAO in the middle mesosphere are affected by planetary Rossby waves [Dunkerton and Delisi, 1985] and/or gravity waves [Sato et al., 2009], which are hemispherically-asymmetric in their occurrence.

Figure 7 is the distribution of the amplitudes of the QBO-like terms. Largest amplitudes occur at middle latitudes at about 0.03 hPa, and another maximum occurs in the tropical upper mesosphere. In fact, the distribution in Figure 7 is very similar to that of the QBO terms for the HALOE temperature data in Remsberg [2008b], indicating that the interannual variability of H₂O is primarily due to transport processes. The QBO amplitudes are somewhat larger in the northern than in the southern hemisphere subtropics, and the minimum values occur at about 15S. These differences may indicate that the wave forcings associated with at least one phase of
the QBO cycle are interacting with the SAO forcings of the northern subtropics more effectively
[Garcia et al., 1997].

At this point it is noted that the MLR analyses herein were conducted independently for each of
the 90 HALOE H2O time series. Therefore, an important measure of the quality of the results in
Figures 3-5 and 7 is the spatial coherence of their patterns with altitude and latitude. Uncertainty
for the coefficients of the terms from the MLR fit to the data is of the order of 0.20 ppmv (2-σ),
which is small compared with the amplitudes of the seasonal terms. Distributions for the QBO
and IA terms are not very significant because their amplitudes are less than 0.22 ppmv (4%)
everywhere. One should also be aware that the estimates of uncertainty assume that the various
terms of the MLR models are orthogonal to each other. That requirement is not met for the 11-yr
and linear trend terms of the 14-yr HALOE time series.

3. Decadal-scale Responses in Water Vapor

Early analyses of the mesospheric response of HALOE water vapor to the variations of solar Ly-
α were provided by Randel et al. [2000] and Chandra et al. [1997]. Randel et al. [2000]
reported a “max minus min” variation of 21% for the period 1992-99, while Chandra et al.
[1997] reported an increase of 41% from January 1992 to December 1995, both at 0.01 hPa. Part
of their differences may be traceable to the HALOE version 19 dataset used by Randel et al.
[2000] versus the version 18 data employed by Chandra et al. [1997]. Their findings may also
have been affected by the underlying trends for H2O that are increasing in the mesosphere
through the 1990s; the trends are more nearly flat thereafter [Nedoluha et al., 2009].
As noted in Section 2, the approach to the SC analyses herein has been to simply fit the HALOE water vapor time series with a sinusoid of 11-yr period and then to check its phase to see how closely it conforms to an estimate of the variations of the direct Ly-α flux. Since H$_2$O is photolyzed most effectively at solar maximum, its 11-yr responses are plotted for solar “max minus min” (as a percent of its average value) and are therefore negative. Figure 8 is a contour plot of that full change in H$_2$O (i.e., twice its amplitude), which varies from about 4% near 0.2 hPa to about 23% at 0.01 hPa, the latter value agreeing most closely with the values of Randel et al. [2000] and Nedoluha et al. [2009]. Values of 4% are just significant at the 2-σ level; the greater percentage values are considered highly significant.

Figure 9 is the phase of the maximum of the 11-yr H$_2$O response (in years past January 1991 or 2002). The dashed contour denotes the 5.5-yr value or July 1996, the approximate time of solar flux minimum (or water vapor maximum). In the middle mesosphere the water vapor maximum is lagging solar flux minimum by about 1 year at middle latitudes and by nearly 2 years in the tropics. However, the phases of those weak amplitude terms are just barely significant, and they are the terms that are most likely to be confounded with the associated linear trend terms (see further discussion in the last paragraph of this section).

Figure 10 is the plot of the so-called SC-like H$_2$O responses. They were obtained by adjusting the 11-yr responses of Figure 8 by the fact that they were not quite in-phase with the Ly-α flux.
forcing—i.e., an adjustment by the \( \cos \left( \frac{t-5.5}{11} \right) \), where \( t \) is the time of the 11-yr water vapor maximum from Figure 9. In effect, this adjustment accounts for the possibility that there are other decadal-scale forcings for the \( \text{H}_2\text{O} \) that were not considered in the MLR model. There is little change for the \( \text{H}_2\text{O} \) responses between Figures 10 and 8 for the upper mesosphere. Those max minus min \( \text{H}_2\text{O} \) percentage variations are opposite in sign but very similar in magnitude to the observed 11-yr changes in the Lyman-\( \alpha \) flux [Tobiska et al., 1997; Deland et al., 2004]. The adjusted, max minus min \( \text{H}_2\text{O} \) variations are altered the most for the tropical middle mesosphere and are now no larger than about 2%. The 11-yr and the SC-like responses are nearly symmetric about the Equator in the uppermost mesosphere. However, the diagnosed responses at middle latitudes are about twice as large in the northern as in the southern hemisphere, indicating a potentially confounding influence from the trend terms.

Model \( \text{H}_2\text{O} \) solar cycle responses agree well with the HALOE findings in the uppermost mesosphere, once an accommodation is made for the fact that the percentage responses for many of the models are referenced to their 11-yr \( \text{H}_2\text{O} \) minimum values rather than to the response average, as in Figures 8 and/or 10 [e.g., Garcia et al., 1984; Huang and Brasseur, 1993; and Schmidt et al., 2006]. The SC-like response profile from Figure 10 at 20N also agrees well with that from the Water Vapor Millimeter-wave Spectrometer (WVMS) instrument at Mauna Loa for the concurrent period of the HALOE data [Nedoluha et al., 2009].
The MLR models include linear trend terms, and Figure 11 is their distribution (in %/decade). Values vary from 12 (or 1.2%/yr) at 40N and 8 (or 0.8%/yr) at 40S to nearly no change at the Equator. Such large values for the middle latitudes of the mesosphere are unphysical compared with the model simulations of about 4%/decade, due primarily to the trends from the oxidized methane [Garcia et al., 2007]. It is also noted that no significant changes in the HALOE instrument have been found that might be contributing to these observed H2O trends and, in particular, their variations with latitude in Figure 11 [Gordley et al., 2009].

The distribution of trends in the tropics to subtropics of Figure 11 is qualitatively consistent with the H2O and CH4 trends of the stratosphere of several years earlier. For example, Randel et al. [2006] reported H2O increases of order 1%/yr in the lower stratosphere from HALOE data for the decade of the 1990s, followed by a decreasing to no trend after 2001. Scherer et al. [2008] found H2O trends from balloon-borne, frostpoint measurements at Boulder of -0.2 to 1.0%/yr for altitudes from 14 to 25 km for the same period with a clear change of trend in 2000/2001. Trends in tropospheric CH4 were variable and generally positive (~0.3%/yr) through the 1990s, but also slowed to near zero thereafter [Dlugokencky et al., 2009]. Correspondingly, the observed positive trends of CH4 for the lower stratosphere slowed to about zero during the HALOE period [Rohs et al., 2006]. It is reasonable to assume from the age-of-air characteristics for the H2O and CH4 entering the lower tropical stratosphere that their trends will be retained (at least to some extent) as that air is transported upward over a period of several years to near the stratopause by the Brewer/Dobson circulation [Shepherd, 2007]. However, because the exchange of air between low and high latitudes is much more efficient in the mesosphere, the
diagnosed HALOE trends of the middle latitudes cannot be due to the changing stratospheric source gases.

The character of the MLR fit at northern middle latitudes is examined further in Figure 12 for 35N and the 0.05-hPa level. A closer look at the annual cycle variations in the data reveals that they are smaller than those from the MLR fit during 1995-97, while they are clearly larger in the data from about 2000-03. In other words, the amplitudes of the seasonal cycles in the H2O data are varying over the 14-yr time period of HALOE. Thus, the residuals that are obtained after the time series data are de-seasonalized will contain some longer-period structures that are being accounted for by the interannual, 11-yr, and linear trend terms of the MLR model. The constraint of the seasonal-cycle fit is contributing to the anomalous character of the diagnosed 11-yr and trend terms.

It is postulated that the rather marked difference for the 11-yr and trend terms of the two hemispheres is also an indicator of the differences for the seasonal exchanges of air between the middle and high latitudes. During winter there is descent of air having low H2O values in the polar vortex. The degree to which that air is transported and/or mixed to lower latitudes depends on the extent to which the vortex remains intact through the winter/spring period, and generally there is more wintertime wave activity propagating to the mesosphere from below in the northern hemisphere [Sato et al., 2009]. Northern hemisphere, mid-winter warming events in the upper stratosphere are accompanied by a cooling in the mesosphere, a weakening or breakdown of the
polar night jet, and an enhanced meridional transport and mixing of the air. Such mid-winter events are rarely found in the southern hemisphere. Pawson and Naujokat [1999] reported that there was very little mid-winter wave activity at NH high latitudes during most of the 1990s, while Manney et al. [2005] found such activity to be prevalent for 6 of the next 7 years. Since H$_2$O has a significant meridional gradient in the middle mesosphere at the mid latitudes (Figure 1), it is reasonable to conclude that the degree to which the seasonal cycles of the model do not match the data in Figure 12 is an important indicator of the response of the transport to those events. Such activity may bear little relation to the solar cycle forcing, although there is no way to know for sure based on this rather short, 14-yr HALOE dataset.

Observations of increasing lower stratospheric H$_2$O trends up to 2001, followed by decreasing trends thereafter, strongly suggest that 14 years is much too short a time for an analysis of its trends. The findings herein from the HALOE dataset also support that contention for the mesosphere. As Garcia et al. [2007] argued, one may need 30-40 years of data before one can estimate a true secular trend in water vapor for the middle atmosphere.

### 4. Implications of the Solar Cycle Responses in H$_2$O

There have been a number of observational and model studies of the effects of water vapor in the upper mesosphere and its relation to the occurrence of PMCs near 0.01 hPa [e.g., Shettle et al., 2009; Sonnemann and Grygalashvyly, 2005]. Although the analyses of the HALOE water vapor responses herein do not quite extend to the high latitudes of the PMCs, Figure 5 indicates that the
AO term has larger percentage responses in the northern than in the southern hemisphere for that region of the upper mesosphere. Maximum H$_2$O mixing ratios occur in the summer at high latitudes. Recall that Figure 9 indicates that PMCs should also occur most frequently at solar minimum, when H$_2$O values are at their maximum. On the other hand, Figure 10 shows that the percentage changes for the SC-like responses of H$_2$O are nearly identical for the two hemispheres near 0.01 hPa, indicating that there should be no hemispheric difference in the SC-like occurrence of PMCs due to water vapor.

The observed greater seasonal occurrence of PMCs in the northern versus the southern hemisphere would be aided by slightly colder temperatures near the summer polar mesopause of the northern hemisphere [Wrotny and Russell, 2006; Hervig and Siskind; 2006]. Figure 13 is the plot of the HALOE AO temperature amplitudes for 10-degree wide latitude bins from 60S to 60N adapted from Remsberg [2007]. Note that although the seasonal sampling from HALOE is barely adequate at the higher latitudes, signal-to-noise values in the mesosphere are much larger for the temperature than for the H$_2$O measurements. Therefore, the MLR analyses were extended to higher latitudes for temperature, and it was found that its AO amplitudes agree closely with those from the earlier satellite temperature climatology of Barnett et al. [1985].

Figure 13 shows that the seasonal temperature variations of the upper mesosphere extend farther into the subtropics for the northern hemisphere—an indication of the associated effects of the net transport for the two hemispheres. Note also that the AO temperature amplitudes at the high
latitudes are larger by up to 4 K in the southern than in the northern hemisphere, potentially leading to formation of more PMC in southern hemisphere summer. But when those AO temperature variations are referenced to the annually-averaged temperatures of Figure 14 that are colder by up to 5 K near 0.01 hPa in the northern versus the southern high latitudes, it is the high latitudes of the northern hemisphere that are actually favored slightly for PMC formation. Thus, it should be clear that if one wants to reconstruct the actual temperature from the MLR fit, one needs to know the constant term and resolve both the annual and semiannual harmonics from the HALOE data time series. Although the seasonal sampling for the HALOE H$_2$O measurements was marginal at the high latitudes where PMCs occur, the combination of slightly colder temperatures plus slightly larger H$_2$O mixing ratios at the nearby latitudes favors the formation of PMC at the northern high latitudes in summer, in accord with earlier findings [Wrotny and Russell, 2006; Hervig and Siskind, 2006].

Remsberg [2008b] found that the HALOE temperatures are also colder at solar minimum than at solar maximum at the higher latitudes near 0.01 hPa. In other words, when the SC-like H$_2$O mixing ratios are at their maximum, the temperatures are coldest. Furthermore, the SC-like, max minus min, temperature responses (though small) are about a factor of 2 greater at the northern than at the southern high latitudes of the upper mesosphere, as shown in Figure 15. Therefore, it is tentatively concluded that the occurrence of PMCs is significantly greater at solar minimum in the northern hemisphere than in the southern hemisphere due to the temperature differences, in accord with the earlier estimates of Hervig and Siskind [2006], Siskind et al. [2005] and Wrotny and Russell [2006]. Even so, it may be that this finding is unique to the HALOE time period, as
opposed to being a regular occurrence [e.g., Luebken et al., 2009]; longer time series are needed to verify that prospect.

Marsh et al. [2003] analyzed HALOE ozone for its response to HOx (and H\textsubscript{2}O) in the upper mesosphere and reported that only its SS (not SR) ozone was sensitive to those changes. They also found significant decreases in HALOE ozone associated with a nearly linear increase of about 1%/yr in the HALOE H\textsubscript{2}O, at least for the period of 1991-2001. However, the results of Figure 11 indicate much weaker H\textsubscript{2}O trends at most latitudes based on the full 14-yr HALOE dataset. It is very likely that the associated ozone trends are smaller, too. The overall response of mesospheric ozone to the H\textsubscript{2}O from HALOE should be reanalyzed and compared with the model simulations of the SC-like responses of ozone [e.g., Schmidt et al., 2006; Marsh et al., 2007; Tsutsui et al., 2009]. Still, the direct effects of the solar cycle forcing for ozone are much smaller than for H\textsubscript{2}O in the upper mesosphere. Thus, the attribution of trends in ozone to any long-term changes in the H\textsubscript{2}O is affected by the precision of the ozone and requires further study.

5. Summary Findings

The HALOE measurements were obtained with a sampling frequency that is adequate for resolving the seasonal and longer-term variations at low and middle latitudes. Its 14-yr (1991-2005) time series of H\textsubscript{2}O were analyzed for those variations in the middle and upper mesosphere. The distribution of the annual average H\textsubscript{2}O shows a decrease from a maximum of about 6.5 ppmv in the mid-mesosphere to 3.2 ppmv near 0.01 hPa, in accord with the effects of the photolysis of H\textsubscript{2}O due to the Ly-\alpha flux. Although SAO cycle amplitudes are hemispherically-
symmetric at low latitudes, AO cycle amplitudes are clearly larger in the northern than the
southern hemisphere. It is presumed that this hemispheric asymmetry is reflective of a stronger
net circulation for the northern latitudes, particularly during winter and springtime.

The response of a periodic, 11-yr term is essentially anti-phased with that of the solar cycle flux
in the upper mesosphere. Its “max minus min” H₂O responses vary from about 4% at 0.2 hPa to
about 23% at 0.01 hPa; they are nearly hemispherically-symmetric in the uppermost mesosphere.
At 20N the profile of the solar cycle (or SC-like) H₂O response from HALOE is in good
agreement with the microwave measurements of Nedoluha et al. [2009] and with numerical
model simulations generally. The 11-yr response in the mid-mesosphere is nearly anti-phased,
lagging that of the solar cycle flux by no more than 1 to 2 years; the response is asymmetric
between the northern and southern hemispheres, however. The associated linear trend terms in
the mid-mesosphere agree with model estimates at low latitudes, but are too large at the middle
latitudes of the northern hemisphere. It was found that the observed seasonal cycle in H₂O had
varying amplitude over that 14-yr period that was not accounted for by the AO terms of the MLR
model. The accompanying, de-seasonalized residuals led to anomalous results for the 11-yr and
trend terms in the northern hemisphere, as a result. Those variations of the observed seasonal
cycle amplitudes are considered an indicator of changes in the meridional transport and mixing
due to the wave forcing from below, although it is unclear whether there is any association with
the solar cycle itself. The distribution of SC-like and trend terms may be unique to the 1991-
2005 timeframe; data over several complete solar cycles are needed in order to know for sure.
Taken together, these analyzed, seasonal and decadal-scale H$_2$O variations may be useful diagnostics for assessing the validity of model transport in the mesosphere.

The combination of high H$_2$O and low temperature supports a higher frequency of occurrence of PMCs at high latitudes of the upper mesosphere during the summer. Although the SC-like variations in the HALOE H$_2$O are nearly hemispherically-symmetric in the upper mesosphere, the concurrent variations in temperature are not. Temperatures are coldest at the higher latitudes of the northern hemisphere in summer and at solar minimum. It is concluded that these conditions are likely the primary reason for a greater occurrence of PMCs in the northern versus the southern hemisphere high latitudes at solar minimum during the HALOE time period.
Acknowledgements. The author recognizes Jim Russell III, HALOE Principal Investigator, the HALOE Science Team, and the many members of the HALOE Project for producing and characterizing the high quality HALOE dataset. He also acknowledges helpful discussions with his colleague, Murali Natarajan, with regard to numerical models of the effects of a solar cycle forcing on mesospheric water vapor. The author has benefitted particularly from the insight and constructive comments of the reviewers of his manuscript. Initial findings from this work were presented at the AMS Middle Atmosphere Meeting, in Stowe, Vermont, in June 2009. Jack Kaye of NASA Headquarters provided support for this work within his Solar Occultation Satellite Science Team (SOSST) study activity.
References


Table 1—Phase of Maximum of First SAO Cycle (in days since Jan 1)

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Figure 1. Time series of bin-averaged HALOE SS (solid) and SR (open) H₂O values at 35N and 0.015 hPa (near 75 km). The oscillating curve is the MLR model fit to those values.

Figure 2. Time series of the data minus model H₂O residuals (in ppmv) of Figure 1.

Figure 3. Pressure versus latitude contour plot of the 14-yr, annual average H₂O mixing ratio (in ppmv). Contour interval is 0.4 ppmv and altitude coordinate is approximate.

Figure 4. As in Figure 3, but for the amplitudes of the semi-annual (SAO) terms as a percentage of the 14-yr average values. Contour interval is 5%.

Figure 5. As in Figure 3, but for the amplitudes of the annual (AO) terms as a percentage of the 14-yr average values. Contour interval is 5%.

Figure 6. As in Figure 1, but for 15N and 0.05 hPa.

Figure 7. As in Figure 3, but for the amplitudes of the quasi-biennial (QBO) terms as a percentage of the 14-yr average values. Contour interval is 0.5%.
Figure 8. As in Figure 3, but for the 11-yr “max minus min” responses, as a percentage of the 14-yr average values. Contour values are negative and their interval is 2%.

Figure 9. Time of the maximum of the 11-yr term for H$_2$O (in years past January 1991 or 2002). The dashed curve denotes 5.5 years (or July 1996), and the contour interval is 0.2 years.

Figure 10. As in Figure 8, but for the solar cycle (or SC-like) “max minus min” H$_2$O responses as a percentage of the 14-yr average values. Contour interval is 2%.

Figure 11. Pressure versus latitude plot of the linear trends for H$_2$O in terms of their percentage changes per decade. The zero contour is dashed, and the contour interval is 1.5%/decade.

Figure 12. As in Figure 1, but for 35N and 0.05 hPa.

Figure 13. Pressure versus latitude plot of the temperature amplitudes for the annual cycle (in K). Contour interval is 2 K.

Figure 14. As in Figure 13, but for the 14-yr, annual average temperatures (in K). Contour interval is 5 K.
Figure 15. As in Figure 13, but for the solar cycle (or SC-like), max minus min, temperatures (in K). The negative and zero contours are dashed, and the interval is 0.5 K.
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