Solar induced variations of odd nitrogen: Multiple regression analysis of UARS HALOE data

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[1] A linear multiple regression statistical model is applied to estimate the solar induced component of odd nitrogen variability in the stratosphere and lower mesosphere using UARS HALOE data for 1991–2003. Consistent with earlier studies, evidence is obtained for a decadal NO_x variation at the highest available latitudes (50° – 70°) that projects positively onto the solar cycle. This variation, which is most statistically significant in the Southern Hemisphere, also correlates positively with the auroral Ap index. It is therefore probably caused by downward transport during the polar night of thermospheric and mesospheric odd nitrogen. In addition, at low latitudes near and above the stratopause, evidence is obtained for an inverse solar cycle NO_x variation. It is suggested that this low-latitude response may be caused primarily by increased photolysis of NO under solar maximum conditions. Throughout most of the rest of the stratosphere, no statistically significant response is obtained. **Citation:** Hood, L. L., and B. E. Soukharev (2006), Solar induced variations of odd nitrogen: Multiple regression analysis of UARS HALOE data, *Geophys. Res. Lett.*, *33*, L22805, doi:10.1029/2006GL028122.

1. Introduction

[2] The observed solar cycle variation of stratospheric ozone is a key constraint on climate models that include solar variability as a forcing mechanism and that account for the existence of the stratosphere. Although changes in UV spectral irradiance are believed to be the primary solar forcing mechanism, the observed ozone variations differ significantly from most current model simulations (*Hood* [2004] and *Soukharev and Hood* [2006], but see also *Lee and Smith* [2003]). In addition to solar UV variations, it is possible that odd nitrogen, which is produced mainly by N_2O oxidation and is the leading source of ozone catalytic losses at most altitudes in the stratosphere, has been influenced by solar variability. It has been suggested that this is the main cause of apparent differences between observed and model-predicted solar cycle ozone variations [*Callis et al.*, 2000, 2001; see also *Rozanov et al.*, 2005; *Langematz et al.*, 2005].

[3] It was originally suggested that direct relativistic (>700 keV) electron precipitation (REP) at middle to high latitudes could be the main cause of solar induced variations of stratospheric odd nitrogen [*Callis et al.*, 1991, and references therein]. In later work, energetic electron precipitation (EEP) at energies ranging from ~4 to 1050 keV has been proposed to be important for solar induced odd nitrogen variations [*Callis et al.*, 1998, 2001]. At lower energies, EEP together with solar proton events (SPE's [see, e.g., *Jackman et al.*, 2005a, 2005b] and solar extreme UV fluxes (EUV) produce odd nitrogen in the high-latitude middle and upper atmosphere, where it can be transported downward during the polar night when photolysis rates are very slow [*Solomon et al.*, 1982]. If this odd nitrogen is subsequently transported to lower latitudes in the stratosphere, a significant modification of the solar cycle variation of stratospheric ozone could occur [*Callis et al.*, 2000]. This possibility is supported by large reported hemispheric NO_2 column changes (35% for the 10°N to 70°N band) between 1985 and 1987 based on SAGE II data [*Callis et al.*, 1998]. In addition to EEP, SPE, and EUV effects on odd nitrogen, another possible source of decadal NO_x variations is photodissociation of NO near 180 and 190 nm [*Minschwaner and Siskind*, 1993]. The latter source would produce NO_x variations out of phase with the solar cycle.

[4] It is generally agreed that NO_x increases caused by SPE's, EEP, and EUV are important for modifying ozone abundances in the wintertime stratospheric polar vortex, especially in the Southern Hemisphere (SH). Observations show that large NO_x abundances above the stratopause produced by these mechanisms can be transported down to the stratosphere at SH polar latitudes in winter [*Siskind and Russell*, 1996; *Callis et al.*, 1996; *Randall et al.*, 1998; *Siskind et al.*, 2000]. At least in some cases, large NO_x enhancements in the polar vortices are probably caused mainly by SPE's [*Randall et al.*, 2001]. However, the importance of particle precipitation for the NO_x abundance in the global stratosphere outside of the polar vortices has been controversial (for further discussion of EEP, see *Siskind* [2002] and *Callis et al.* [2002]).

[5] Interannual variability of NO_x in the mid-stratospheric SH polar vortex has been found to correlate well with the auroral Ap index, which is a measure of the total particle precipitation flux (SPE's + EEP) [*Randall et al.*, 1998; *Siskind et al.*, 2000]. The Ap index correlates positively with the solar cycle during the last several cycles although the variation is more irregular. It also correlates positively with solar wind plasma speed (R = 0.7 for annual means, 1964–2005). The latter has previously been shown to correspond closely with EEP for E >30 keV on both short and long time scales [*Callis et al.*, 1998, 2001].

[6] Recently, several sensitivity studies using three-dimensional chemistry climate models have been conducted to gauge the effect of NO_x produced during EEP events on stratospheric ozone and temperature variability, including that occurring on the solar cycle time scale [*Rozanov et al.*, 2005; *Langematz et al.*, 2005]. While the Rozanov et al. study was not specifically a solar cycle study, both studies

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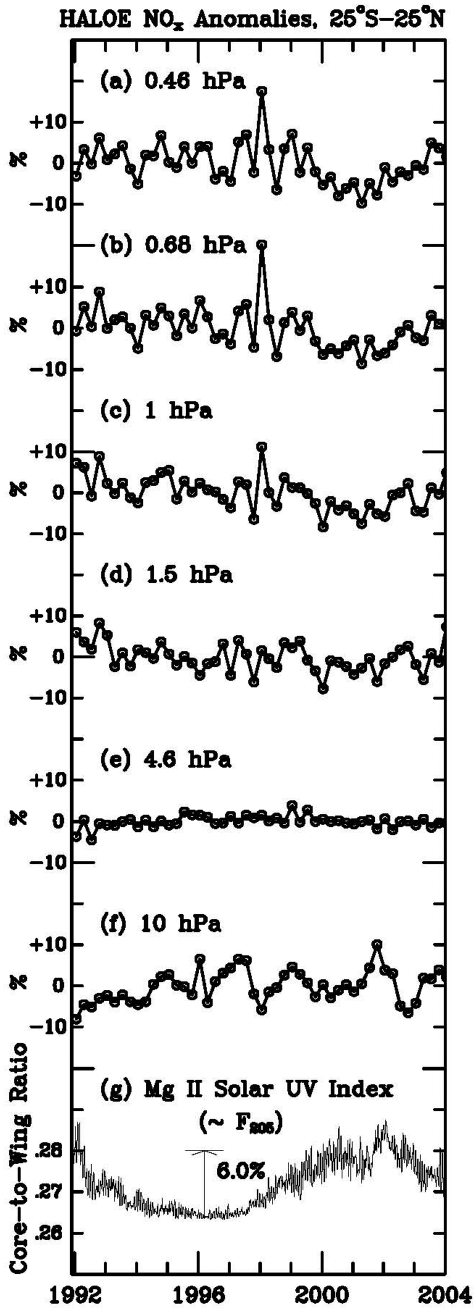

Figure 1. Comparison of 3-month time series of tropically averaged HALOE NO + NO_2 sunset anomalies (deviations from long-term means for each season) at six pressure levels. Also plotted is the daily Mg II core-to-wing ratio, a close proxy for solar UV variations.

suggest that this NO_x source and its transport from the mesosphere to the stratosphere are important for decadal global ozone variations. In apparent support of these model calculations, observational evidence for a possible strong *positive* solar cycle variation of ozone in the polar middle stratosphere (~30 km altitude; 70° – 90° latitude) in winter that correlates inversely with energetic (E >2 MeV) electron fluxes at geosynchronous orbit has recently been reported [*Sinnhuber et al.*, 2006].

[7] In this paper, an initial effort is reported to investigate empirically the solar contribution to global stratospheric odd nitrogen variability using 12 years of measurements by the Halogen Occultation Experiment (HALOE) on the Upper Atmospheric Research Satellite (UARS).

2. Data Description and Time Series Comparisons

[8] We use the Version 19 UARS HALOE data [e.g., *Remsberg et al.*, 2001] for the period from December 1991 to December 2003. The ending date is chosen to maximize the length of the time series while minimizing the effects of increasingly sparse measurements during the final few years of the mission. For this data set, which is available from the http://haloedata.larc.nasa.gov internet site, solar occultation radiance measurements are used to obtain the vertical profiles of O_3, HCl, HF, CH_4, H_2O, NO, NO_2, aerosol extinction, and temperature. The vertical resolution of the data is approximately 3 km and measurements typically extend from the upper troposphere to the lower mesosphere.

[9] Like other solar occultation instruments, the HALOE measurements have reduced spatial and temporal sampling compared with nadir-viewing sounders. Specifically, on a given day, essentially two latitudes are sampled, one during sunrise events and the other during sunset events. It takes about 1.5 months for the sampling latitude to shift from one latitudinal extreme to the other (~50°–80°S to 50°–80°N, depending on the time of year). For either sunrise or sunset events, there are about 15 sampling opportunities per day with successive locations shifted by about 25° in longitude and a fraction of a degree in latitude. Thus, it is possible to calculate reasonably accurate daily zonal means only at the two latitudes that are sampled on a given day. At a given latitude, one or two daily zonal means are available for any given month and year. Because of this, it is not possible to calculate true monthly zonal means using the HALOE data. To reduce this problem, we have therefore elected to calculate 3-month zonal averages (e.g., DJF, MAM, JJA, and SON) within 10- degree latitude bands by averaging together all available "daily zonal means". A minimum of 5 measurements within a given latitude band is required before a "daily zonal mean" is accepted as valid.

[10] As summarized, for example, by *Dessler* [2000], total reactive odd nitrogen, NO_y, is defined to be the abundance of all N atoms that are not bound up in N_2 or N_2O. The "active" component of NO_y, i.e., those compounds that participate in catalytic cycles that destroy ozone, is defined as $[NO_x] = [NO] + [NO_2] + [NO_3]$. During the daytime, $[NO_3]$ is negligible so that, to a very good approximation, $[NO_x] \simeq [NO] + [NO_2]$. During the night, the presence of NO_3 allows combination with NO_2 to produce N_2O_5, effectively reducing the abundance of NO_x. Although the process is reversed in the daytime, the conversion from N_2O_5 to NO_2 complicates the interpretation of HALOE sunrise measurements of [NO] + $[NO_2]$. For this reason, only sunset data are used here.

[11] Figure 1 compares time series of HALOE [NO] + $[NO_2]$ sunset (~ $[NO_x]$) anomalies (deviations from long-term seasonal means) at low latitudes (25°S to 25°N) and six selected pressure levels in the stratosphere and lower mesosphere. Long-term changes in NO_x in the tropical

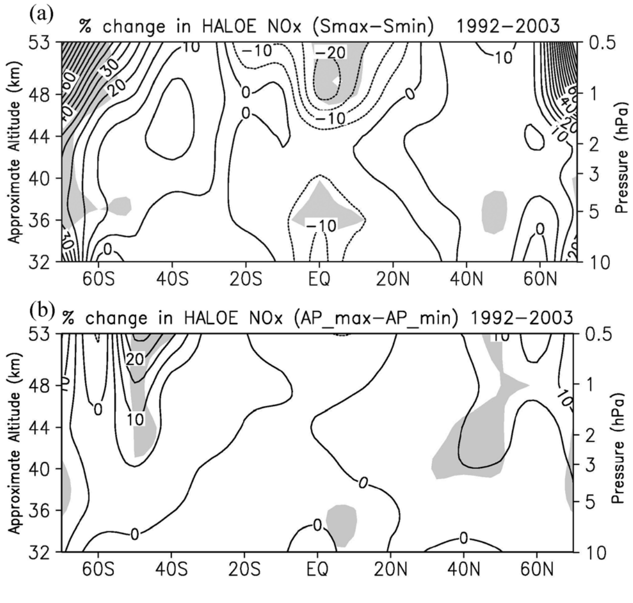

Figure 2. Contour maps of the annual mean HALOE NO_x solar regression coefficients (see the text). (a) The Mg II solar UV index is used as a measure of solar forcing; (b) the auroral Ap index is used. Shaded areas are significant at the 2σ (95% confidence) level.

upper stratosphere near 1.5 hPa measured by HALOE during the early 1990's may have been caused, at least in part, by changes in tropical upwelling rates or horizontal mixing associated with aerosol heating following the Pinatubo volcanic eruption [*Nedoluha et al.*, 1998]. However, in the uppermost stratosphere and lower mesosphere (0.46, 0.68, and 1 hPa), an apparent decadal variation is present (especially at 0.46 and 0.68 hPa) that is approximately out of phase with the solar cycle. In particular, there is a noticeable decrease in 2000–2002, coinciding roughly with the maximum of solar cycle 23.

3. Multiple Regression Analysis

[12] Following earlier analyses of long-term ozone data sets [e.g., *Hood*, 2004, and references therein], we assume that the temporal behavior of zonally averaged NO_x can be represented by a multiple linear regression model of the form,

$$NO_x(t) = \mu(i) + \beta_t t + \beta_q u_{30}(t - L) + \beta_s S(t) + \varepsilon(t) \quad (1)$$

where t is the time in 3-month increments, $\mu(i)$ is a seasonal term equal to the long-term mean for the ith season of the year (i = 1, 2,. . .4); u_{30} is the 30 hPa equatorial zonal wind obtained from the National Centers for Environmental Prediction (NCEP) reanalysis data set; L is a lag time required to produce a maximum positive or negative correlation between the NO_x time series at a given location and the NCEP 30 hPa equatorial wind; $S(t)$ is a time series representing solar forcing; and $\varepsilon(t)$ is a residual error term. The coefficients β_t (linear trend), β_q (QBO), and β_s (solar) are determined by least squares regression. We consider here two possible solar forcing functions. First, assuming that the primary solar forcing is solar UV and EUV fluxes, we take $S(t)$ = $MgII(t)$, where $MgII(t)$ is the core-to-wing ratio of the solar Mg II line at 280 nm based on Nimbus 7 SBUV, NOAA 9 and 11 SBUV/2, and UARS SUSIM data [e.g., *Viereck and Puga*, 1999]. Second, assuming that the primary solar forcing is EEP and SPE's, we take $S(t)$ = $Ap(t)$, where $Ap(t)$ is the geomagnetic Ap index obtained from http://www.ngdc.noaa.gov/stp/GEOMAG/kpap.shtml. As noted in the Introduction, an alternate possible proxy for EEP is solar wind plasma speed [*Callis et al.*, 1998]. However, solar wind speed correlates closely with the Ap index during the 1992–2003 period (R = 0.91 for annual means). Therefore, only the Ap index is considered here. As in previous work, the residual error term ε (t) is modeled as a first-order autoregressive process, i.e., $\varepsilon(t) = r\varepsilon(t\text{-}1) + w(t)$, where $w(t)$ is white noise and r is determined in an initial application of (1) [see, e.g., *Neter et al.*, 1985].

[13] Figure 2 shows β_s calculated by applying (1) to the 3-month zonally averaged HALOE NO_x data over the 1992 – 2003 time period. In Figure 2a, $S(t) = MgII(t)$; in Figure 2b, $S(t) = Ap(t)$. Only coefficients at 10 hPa and above are shown because of increased data sparsity below this level. At a given location, β_s is defined as the % change in zonal mean NO_x concentration between solar minimum and maximum. For the MgII index, minimum and maximum values are taken as 0.2650 and 0.2819, respectively. For the Ap index, the corresponding values are 11 and 19.

[14] The regression coefficients of Figure 2a are statistically insignificant throughout much of the stratosphere. In the middle stratosphere, several small shaded areas indicating statistical significance are present. However, repetitions of the analysis using slightly different processing methods (e.g., requiring at least 10 measurements to calculate a daily zonal mean) show that these apparent responses are not very robust. An upper limit on negative solar cycle variations of NO_x in the tropical middle stratosphere (5 hPa) of ~10% at all latitudes <60° may be estimated based on these results.

[15] As expected from Figure 1 (especially 0.46 and 0.68 hPa), negative coefficients are seen in Figure 2a in the tropical upper stratosphere and lower mesosphere with amplitudes of −15 to −20%. At the stratopause near the equator, the coefficient amplitudes are especially large (−20%) and significant. In this case, repetitions of the analysis using different processing methods supports the reality of the tropical response near the stratopause. In particular, we investigated whether limited sampling (sunset only) combined with the existence of a semi-annual oscillation in NO_x could have artificially produced a decadal variation. However, tests using both sunset and sunrise data to increase the sampling confirmed that the decadal variation did not change. On the other hand, the latitude of the maximum response varies between 20°S and 20°N depending on the details of the processing. Therefore, the location of the maximum negative response near the equator in Figure 2a is not well-determined.

[16] A statistically significant positive response with amplitude as high as +70% is seen in Figure 2a in the SH lower mesosphere at the highest available latitudes (up to 70°S). This positive response extends downward to the middle stratosphere with amplitudes of 20% – 30%. Positive coefficients are also obtained in the NH subpolar lower mesosphere but are not quite significant. The latter signals are not sensitive to details of the processing.

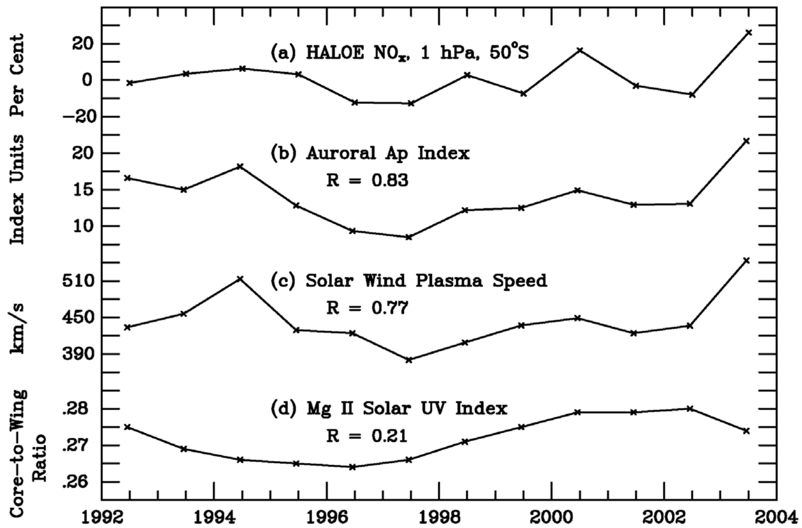

Figure 3. Comparison of (a) yearly averaged NO_x deviations at 1 hPa, 50°S with similarly averaged (b) Ap index, (c) solar wind plasma speed (obtained from http://omniweb.gsfc.nasa.gov/), and (d) the Mg II index. Correlation coefficients (R) are indicated.

[17] Figure 2b shows the NO_x solar regression coefficient calculated using $S(t) = Ap(t)$. In contrast to Figure 2a, no statistically significant response is obtained at low to middle latitudes. In the upper stratosphere and lower mesosphere, statistically significant positive responses are obtained only at extratropical latitudes in both hemispheres. The latitude of maximum response is somewhat lower than obtained in Figure 2a. Figure 3 compares time series of yearly averaged HALOE NO_x deviations at 1 hPa, 50°S to the Ap index, solar wind plasma speed, and Mg II, providing additional evidence that particle precipitation contributes to the observed NO_x interannual variations. 50°S is the highest southern latitude where continuous HALOE measurements are available for all four seasons over the 1992–2003 period.

4. Discussion and Conclusions

[18] The evidence from HALOE data (Figure 2) for a decadal NO_x variation at high latitudes that projects positively onto the solar cycle (as represented either by MgII or Ap) is most easily interpreted as being a consequence of production by EEP, SPE's, and EUV followed by downward transport during the polar night. As found previously using HALOE data, the observed variation is strongest in the SH polar region, probably because of different dynamics (i.e., reduced mixing) as compared to the Northern Hemisphere [*Randall et al.*, 1998; *Siskind et al.*, 2000]. At low latitudes in the lower mesosphere and stratopause region, there is evidence (Figure 2a) for an inverse NO_x solar cycle variation. Since production by particle precipitation (EEP and SPE's) near solar maximum apparently dominates in the polar regions, an EEP source of the negative NO_x signal in the tropics is unlikely. Therefore, we suggest that photolytic destruction of NO near solar maximum is the most likely explanation for this signal. Tests of this interpretation would require detailed modeling.

[19] The present results imply that decadal variations of NO_x, regardless of their source, played a minor or negligible role in the solar cycle variation of stratospheric ozone at middle and low latitudes during the 1992–2003 period. Although final confirmation must await a longer NO_x data record, this provisional conclusion does not support previous proposals that EEP induced changes in NO_x are the main cause of differences between observed and model-predicted solar cycle ozone variations. Although an inverse solar cycle NO_x variation is apparently detected near and above the stratopause, ozone catalytic losses are dominated at these altitudes by HO_x destruction; NO_x destruction is smaller by a factor of about 10 at 1 hPa. The upper limit on solar cycle NO_x variations in the tropical middle stratosphere (~10%) also implies a minor contribution to decadal ozone variability in this region.

[20] In general, these results contrast with sensitivity studies indicating potentially large effects of EEP-induced NO_x variations on the solar cycle variation of global stratospheric ozone [*Rozanov et al.*, 2005; *Langematz et al.*, 2005]. They are also difficult to reconcile with observational evidence recently reported by *Sinnhuber et al.* [2006] using > 2 MeV electron flux at synchronous orbit as a proxy for EEP. However, the latter flux does not correlate well with Ap and may not be completely representative of the precipitation rate of lower energy electrons and solar protons. Also, their study focused mainly on the 800 K (~ 30 km) level and on latitudes higher than those considered here.

[21] **Acknowledgments.** The UARS HALOE data were obtained from the NASA Langley Research Center UARS data center http://haloedata.larc.nasa.gov). We thank Ellis Remsberg for important advice and assistance in the acquisition and processing of the HALOE data. Constructive criticisms by Ulrike Langematz, Linwood Callis, Charles Jackman, and an anonymous reviewer are appreciated. This material is based upon work supported by the National Science Foundation under grant ATM-0424840. Additional support from the NASA Living With a Star Research Program is also appreciated.

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