



## 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<sub>x</sub> 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<sub>x</sub> 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<sub>2</sub>O 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

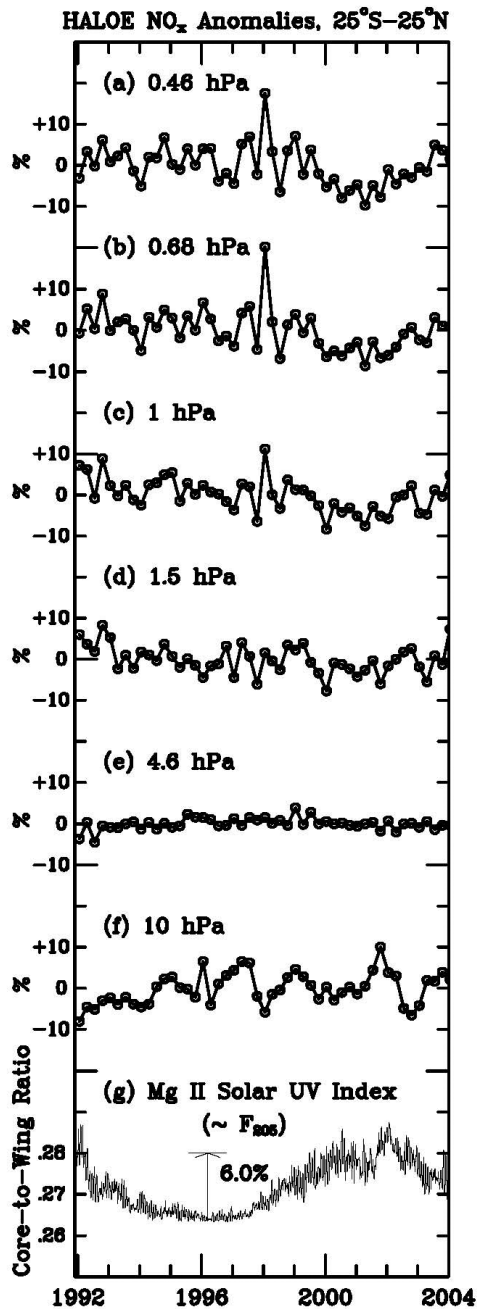
been proposed to be important for solar induced odd nitrogen variations [Callis *et al.*, 1998, 2001]. At lower energies, EEP together with solar proton events (SPE's [see, e.g., Jackman *et al.*, 2005a, 2005b]) and solar extreme UV fluxes (EUV) produce odd nitrogen in the high-latitude middle and upper 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<sub>2</sub> 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<sub>x</sub> variations is photodissociation of NO near 180 and 190 nm [Minschwaner and Siskind, 1993]. The latter source would produce NO<sub>x</sub> variations out of phase with the solar cycle.

[4] It is generally agreed that NO<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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  $\text{NO} + \text{NO}_2$  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  $\text{NO}_x$  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 ( $\sim 30$  km altitude;  $70^\circ - 90^\circ$  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).

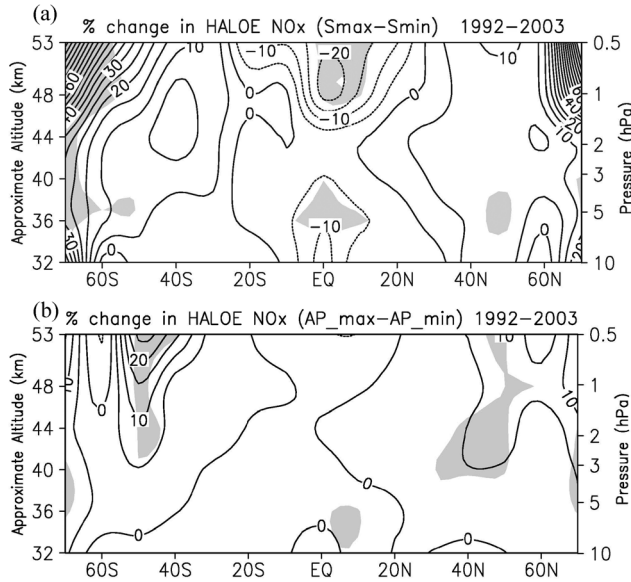
## 2. Data Description and Time Series Comparisons

[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  $\text{O}_3$ , HCl, HF,  $\text{CH}_4$ ,  $\text{H}_2\text{O}$ , NO,  $\text{NO}_2$ , 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 ( $\sim 50^\circ - 80^\circ\text{S}$  to  $50^\circ - 80^\circ\text{N}$ , 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  $25^\circ$  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,  $\text{NO}_y$ , is defined to be the abundance of all N atoms that are not bound up in  $\text{N}_2$  or  $\text{N}_2\text{O}$ . The “active” component of  $\text{NO}_y$ , i.e., those compounds that participate in catalytic cycles that destroy ozone, is defined as  $[\text{NO}_x] = [\text{NO}] + [\text{NO}_2] + [\text{NO}_3]$ . During the daytime,  $[\text{NO}_3]$  is negligible so that, to a very good approximation,  $[\text{NO}_x] \simeq [\text{NO}] + [\text{NO}_2]$ . During the night, the presence of  $\text{NO}_3$  allows combination with  $\text{NO}_2$  to produce  $\text{N}_2\text{O}_5$ , effectively reducing the abundance of  $\text{NO}_x$ . Although the process is reversed in the daytime, the conversion from  $\text{N}_2\text{O}_5$  to  $\text{NO}_2$  complicates the interpretation of HALOE sunrise measurements of  $[\text{NO}] + [\text{NO}_2]$ . For this reason, only sunset data are used here.

[11] Figure 1 compares time series of HALOE  $[\text{NO}] + [\text{NO}_2]$  sunset ( $\sim [\text{NO}_x]$ ) anomalies (deviations from long-term seasonal means) at low latitudes ( $25^\circ\text{S}$  to  $25^\circ\text{N}$ ) and six selected pressure levels in the stratosphere and lower mesosphere. Long-term changes in  $\text{NO}_x$  in the tropical



**Figure 2.** Contour maps of the annual mean HALOE  $\text{NO}_x$  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  $2\sigma$  (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  $\text{NO}_x$  can be represented by a multiple linear regression model of the form,

$$\text{NO}_x(t) = \mu(i) + \beta_t t + \beta_q u_{30}(t-L) + \beta_s S(t) + \varepsilon(t) \quad (1)$$

where  $t$  is the time in 3-month increments,  $\mu(i)$  is a seasonal term equal to the long-term mean for the  $i$ th season of the year ( $i = 1, 2, \dots, 4$ );  $u_{30}$  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  $\text{NO}_x$  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  $\beta_t$  (linear trend),  $\beta_q$  (QBO), and  $\beta_s$  (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,

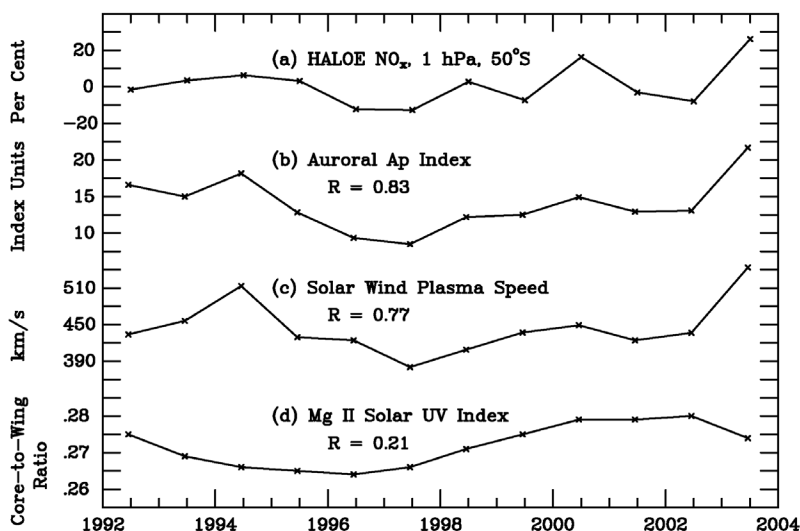
we take  $S(t) = \text{MgII}(t)$ , where  $\text{MgII}(t)$  is the core-to-wing ratio of the solar Mg II line at 280 nm based on Nimbus 7 SBUV, NOAA 9 and 11 SBUV/2, and UARS SUSIM data [e.g., Viereck and Puga, 1999]. Second, assuming that the primary solar forcing is EEP and SPE's, we take  $S(t) = \text{Ap}(t)$ , where  $\text{Ap}(t)$  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  $\varepsilon(t)$  is modeled as a first-order autoregressive process, i.e.,  $\varepsilon(t) = r\varepsilon(t-1) + w(t)$ , 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  $\beta_s$  calculated by applying (1) to the 3-month zonally averaged HALOE  $\text{NO}_x$  data over the 1992–2003 time period. In Figure 2a,  $S(t) = \text{MgII}(t)$ ; in Figure 2b,  $S(t) = \text{Ap}(t)$ . Only coefficients at 10 hPa and above are shown because of increased data sparsity below this level. At a given location,  $\beta_s$  is defined as the % change in zonal mean  $\text{NO}_x$  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  $\text{NO}_x$  in the tropical middle stratosphere (5 hPa) of  $\sim 10\%$  at all latitudes  $< 60^\circ$  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  $\text{NO}_x$  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  $20^\circ\text{S}$  and  $20^\circ\text{N}$  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  $70^\circ\text{S}$ ). 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub>, 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<sub>x</sub> data record, this provisional conclusion does not support previous proposals that EEP induced changes in NO<sub>x</sub> are the main cause of differences between observed and model-predicted solar cycle ozone variations. Although an inverse solar cycle NO<sub>x</sub> variation is apparently detected near and above the stratopause, ozone catalytic losses are dominated at these altitudes by HO<sub>x</sub> destruction; NO<sub>x</sub> destruction is smaller by a factor of about 10 at 1 hPa. The upper limit on solar cycle NO<sub>x</sub> 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<sub>x</sub> variations on the solar cycle variation of global stratospheric ozone [Rozañov *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.

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