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Observed and calculated mesospheric NO, 1992–1997

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[1] Mesospheric nitric oxide as observed by the Halogen Occultation Experiment (HALOE) and calculated by the Langley Research Center two-dimensional chemical transport model are compared on a daily and collocated basis for the period 920101 through 971231. Results show excellent agreement when energetic electron precipitation (EEP) from the outer trapping region of the magnetosphere is included. A simulation using only an upper boundary condition derived from the HALOE, but not explicitly including EEP, is deficient in NO at altitudes above 60 km. The contribution to the stratosphere of odd nitrogen formed by EEP in the mesosphere is significant and is approximately three times the contribution due to the HALOE upper boundary condition (HUBC) which approximates auroral electron precipitation, and solar EUV and solar X-ray effects on NO formation. *INDEX TERMS:* 341 Atmospheric Composition and Structure: Middle Atmosphere—constituent transport and chemistry (3334), 342 Atmospheric Composition and Structure: Middle Atmosphere—energy deposition, 2455 Ionosphere: Particle precipitation

1. Introduction

[2] Studies [*Callis et al.*, 1996a,b, 1998a,b, 2001; and *Callis and Lambeth*, 1998] have demonstrated with observations that energetic electron precipitation (EEP, 4 keV $\leq$ E $\leq$ 1 MeV) from the outer trapping regions of the magnetosphere can lead to significant increases in nitric oxide (NO) in the mesosphere and lower thermosphere. They, and *Rinsland et al.* [1996], *Siskind et al.* [1997], *Randall et al.* [1998], and *Siskind et al.* [2000] have also shown that this may be followed, during periods of descent, by transport into the stratosphere reaching levels as low as ≈25–30 km and contribute to the odd nitrogen (NO_y = NO + NO_2 + 2 × N_2O_5 + HNO_3 + $ClNO_3$ + HNO_4 + NO_3) of the stratosphere.

[3] The importance of EEP to the stratospheric ozone (O_3) and NO_y budgets has been assessed using two-dimensional chemical transport simulations including most processes thought to be important to their distributions and variability [*Callis et al.*, 2001]. The simulations were tested against a variety of observed stratospheric parameters from 1979 through 1997 and found to be in good agreement when the polar source of NO_y, primarily due to EEP, was included. Results of these simulations suggest that EEP, formed in the lower thermosphere and the mesosphere and transported into the stratosphere, has a significant effect on global O_3 and NO_y and must be included in simulations and analyses for an unambiguous understanding of their variations in the stratosphere.

[4] Given the potential significance of the above cited results, it is important to understand the degree to which simulated mesospheric NO, with and without EEP, agrees with the NO observed by the HALOE during the period 1992 through 1997. Some general comparisons between NO observed by HALOE and simulated NO have been made [*Siskind et al.*, 1997]. To the authors' knowledge, however, no detailed collocated comparisons of NO observed by HALOE with the NO from simulations including the effects of electron precipitation from auroral processes as well as electrons precipitating from the outer trapping regions of the magnetosphere, have been made to date. Such a comparison is the purpose of this letter.

2. HALOE NO Observations

[5] HALOE, which is aboard the Upper Atmosphere Research Satellite (UARS), observes NO throughout the mesosphere and into the thermosphere. The HALOE experiment has been described by *Russell et al.* [1993], and the validation of the NO, which is observed in solar occultation at sunrise and sunset, has been described by *Gordley et al.* [1996]. The latitudes observed by HALOE vary on a day-by-day basis and, it should also be noted, that from one year to the next the seasonal coverage provided by HALOE shifts ≈ five days/year. As a result of these two considerations, care must be taken when comparisons are made between long-term simulations and observed HALOE data.

[6] In making comparisons between simulated and observed NO, we follow the approach described in *Callis et al.* [1998b, 2001] and interpolate simulated results to the date and latitude of the daily averaged HALOE NO observations. Averages shown in this work will be averages of collocated scans of the HALOE NO and the simulated NO. Biases associated with the nature of the HALOE coverage, and introduced by averaging in other ways are avoided in this manner. Comparisons are made only with the HALOE sunset data in order to be consistent with the stratospheric comparisons made in *Callis et al.*, noted above.

3. Simulations

[7] Three simulations are used in the present work. The simulation which is referred to as C3 is the full, or base, simulation and, together with the two-dimensional chemical transport code, is described in detail in *Callis et al.* [2001] as Run 3. A simulation herein referred to as C2 is identical to C3 except the effects of EEP have been removed. Finally, simulation

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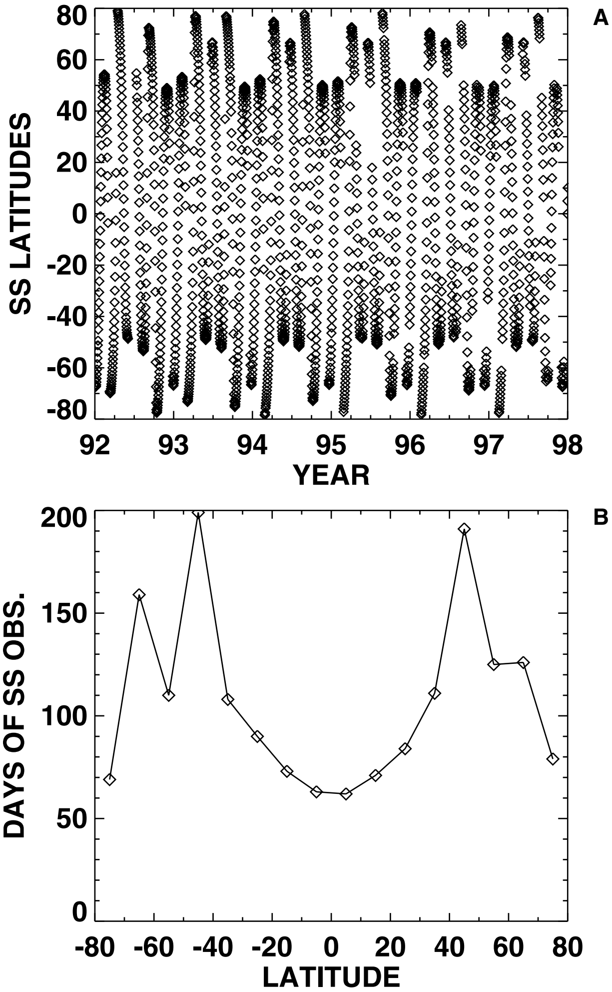

Figure 1. (a) Latitude-time locations of day-averaged sunset HALOE observations. (b) Distribution of the number of sunset observations within 10° latitude bins for the period 920101 through 971231.

C1 is identical to Run 1 described in *Callis et al.* It is identical to C3 except that it includes no EEP and has zero flux of NO_y at the upper boundary.

4. Comparison of Observed and Simulated NO

[8] Figures 1a and 1b illustrate, respectively, the HALOE sunset latitude-time coverage and the distribution with latitude of the number of days observed within 10° latitude bands for the period 920101 through 971231. The most highly sampled latitudes are between 40°–60° in both hemispheres. HALOE does not observe high latitudes during wintertime.

[9] Figures 2a–2c provide comparisons of the simulated and observed NO for three latitude bands and for the period 920101–971231. (For the simulations, NO_y is used as a proxy for NO, which in the mesosphere, is not determined directly in the model. This is quite a good approximation above ≈55 km.) The symbols are the average for the period of the daily-averaged signal to noise ratio (S/N) for the HALOE data. The error bars shown below 60 km are taken from the NO validation paper by *Gordley et al.* [1996]. Systematic errors for NO above 60 km (not shown) are estimated to be 15–20% [Private Communication, L. L. Gordley, 2001]. Two simulations are compared on these figures, C3 and C2. Figures 2a and 2c illustrate good agreement when the effects of electron precipitation are included. Without the inclusion of the electrons, the simulations significantly underestimate the mesospheric NO (by as much as a factor of seven).

[10] For the 40°S to 40°N latitude band, Figure 2b, both simulations show similar results and significantly underestimate the observed NO between 65 and ≈80 km. Most of this discrepancy occurs between ±20°. The disagreement may be

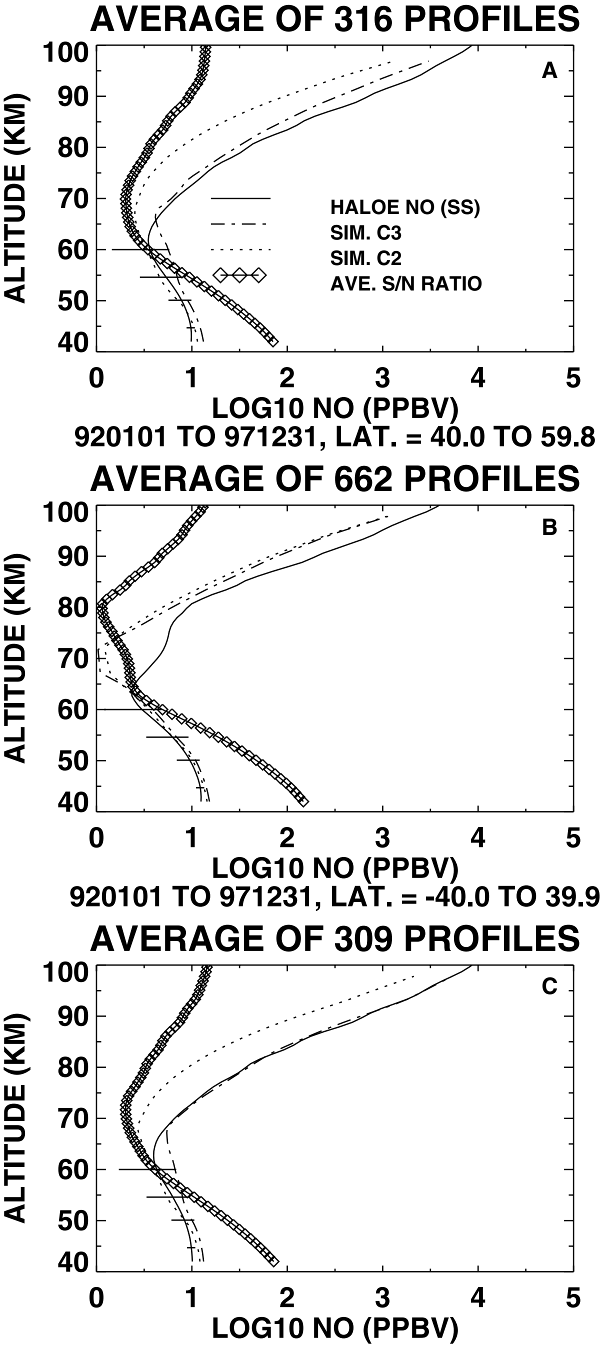

Figure 2. (a) Comparison of collocated NO profiles, as observed by HALOE and as simulated, averaged over the period 920101 through 971231 and for 40°N to 60°N. (b) Same as for (a) except for 40°S to 40°N. (c) Same as for (a) except for 40°S to 60°S.

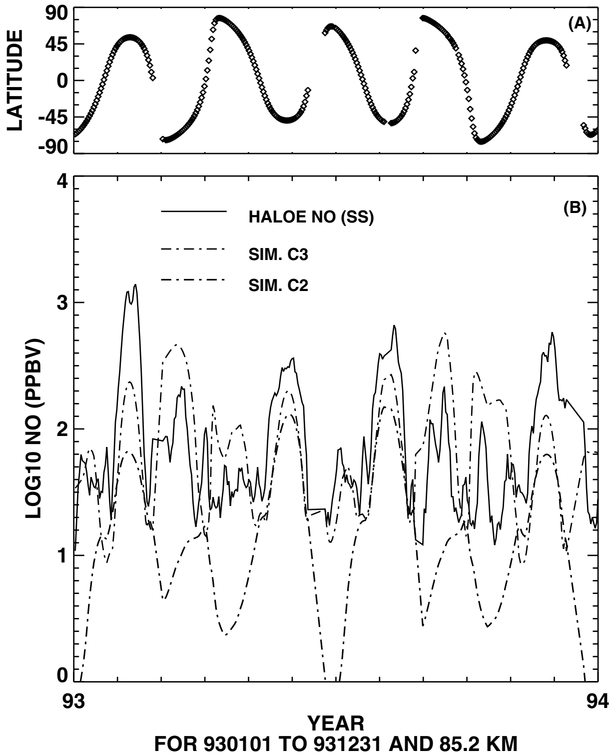

Figure 3. History of observed and simulated NO at sunset and 85.2 km for 1993. The top panel illustrates the latitudes of the HALOE sunset observations.

due in part to the relatively low S/N since noise is 40% to 80% of the total signal in this region. It may also be due in part to the patching together of the stratospheric and mesospheric transport fields near the stratopause. Observed temperatures are used in the development of the stratospheric transport fields, while the mesospheric transport fields are developed using a repeating climatological temperature distribution. Beyond this, the discrepancy is not understood. The similarity of the simulations with and without electron precipitation and within this latitude band is expected, however, since the effects of the electrons occur predominantly at the higher latitudes [*Callis et al.*, 1998a].

[11] Several points should be noted when considering the lower-mesosphere upper-stratosphere comparisons shown on Figure 2. Comparisons below ≈53 km should not be made since, as noted earlier, what is shown as simulated NO is in fact NO_y. Above 55 km, NO_y is essentially all NO. Below 53 km other NO_y constituents begin to become important compromising any comparisons. This explains some of the high bias of the simulations between 42–53 km. Above 60 km and below 70–75 km (80–85 km for the 40 S to 40 N comparisons), the S/N shown range from ≈1.2 to 2.5 indicating that within these regions 40% to 80% of the total signal is noise. Caution must also be exercised in interpreting comparisons within these regions. This problem is most severe for the comparisons shown in Figure 2b.

[12] Figure 3 shows a comparison of the history of the NO observed by HALOE for 1993 compared with two simulations. The comparison of C3 with the data is in good agreement with differences reflecting tidal effects and/or the effects of gravity waves, both of which will contribute to the variability in mesospheric NO and which are not explicitly included in the simulations. The large somewhat irregular variations of the observed NO reflect the shifting latitudinal coverage of HALOE together with the effects of a pronounced 27-day period in the flux of the precipitating electrons as driven by the high speed solar wind streams (e.g. see Figure 2, *Callis et al.* [2001]).

[13] Simulation C2 is clearly deficient. The discrepancy between the HALOE data, observed early in the year, at mid-year and at the end of the year, all three being observed at summertime high latitudes, and the NO from C2, is striking and illustrative. This season at these high latitudes has relatively long days and experiences a slow upward advective motion. The photochemical loss of NO is relatively rapid. Without the presence of the *in situ* source of NO_y due to the energy deposited by the EEP, the NO_y levels are significantly depleted, being lower than the observations by as much as a factor of 50. With the presence of the *in situ* NO_y source in C3, the agreement is quite good. Averaged over the year, the simulation C3 is in relatively good agreement with the observations. Simulation C2 is, however, significantly lower than the observations. Clearly, the effects of EEP must be taken into account. Similar comparisons are found for other years and for other altitudes where the signal to noise ratio is adequate.

[14] A question frequently raised concerns the relative contributions of the auroral electron precipitation ($E \leq 20-30$ keV) and electrons precipitating from the outer trapping regions of the magnetosphere ($5-10$ keV $\leq E \leq 10$ MeV). Simulation C2, without electron precipitation but with the HUBC, roughly approximates the inclusion of the effects of solar X-rays and EUV as well as the auroral electrons. To illustrate the relative effects of EEP and the HUBC, an average of NO_y between 70°S and 70°N and for altitudes between 25 and 50 km has been calculated for simulations C1, C2, and C3. Adding the HUBC to the C1 simulation gives a 4.1% increase in the above noted average of stratospheric NO_y. Then, adding the effect of the electrons leads to an additional increase of NO_y of 11.5% for an overall increase of 15.9%. Of this overall increase in NO_y, ≈26% is due to the HUBC, and, to the extent that the approximation is valid, due to solar X-rays, EUV flux, and auroral effects. This is in essential agreement with a simulation (not published or discussed herein) carried out as in C3 but with the energy deposition due to electron precipitation set to zero at altitudes less than 90 km, an altitude below which few direct effects of solar X-rays, EUV flux, and auroral effects are experienced.

[15] To provide a sense of how the relative effects are distributed in latitude and altitude, Figure 4 is presented illustrating the ratio of

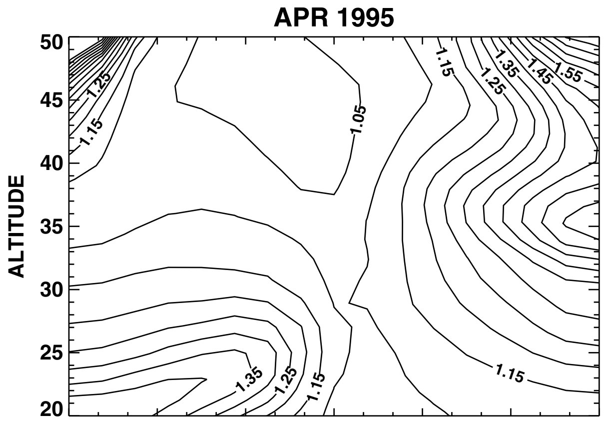

Figure 4. Latitude and altitude contours of the ratio of NO_y. NO_y for simulation C3 (full simulation) is divided by NO_y from C2 (HUBC but no EEP).

stratospheric NO_y for C3/C2. With the inclusion of the electron precipitation from the outer trapping region, increases of NO_y of up to a factor of two are calculated at the highest latitudes. Significant increases are found at all altitudes and over most of the latitude ranges.

5. Summary and Conclusions

[16] Collocated and averaged comparisons of two simulations of mesospheric NO (C2 and C3) have been made with those observed at sunset by the HALOE. The agreement is quite good (where adequate S/N exists) with the inclusion of the effects of electrons precipitating into the atmosphere from the outer trapping regions of the magnetosphere. Without these effects, the simulated NO is significantly lower than the observed values. Between 55 and 70–75 km, attention must be paid to the error bars and the S/N associated with the HALOE data when comparing simulations and observations. The contribution to stratospheric NO_y from the mesosphere is significant ($\approx$16% above 25 km and between 70°S and 70°N) and is predominantly (74%) due to the inclusion of the precipitating electrons from the outer trapping region of the magnetosphere, the remainder being due to the HUBC. Previous results [*Callis et al.*, 1998b, 2001] have found that the mesospheric contributions of NO_y to the stratosphere have significant effects on O_3 on global scales, especially above 25 km. The comparisons presented herein lend confidence to the manner in which the mesospheric NO_y is formed and transported. These comparisons taken together with the numerous comparisons presented for the stratosphere in *Callis et al.* [2001] (using the same simulations) also lend confidence to the validity of the simulated transport of NO_y from the mesosphere to the stratosphere. Unfortunately, direct observations of the bulk of such transport (which could be compared with the simulations), are not possible using the HALOE data. During periods of near maximum descent rates at high latitudes, HALOE observations are available only equatorward of $\approx$52°, a restriction that persists for approximately 170 days. The comparisons herein also indicate that energetic electron precipitation from auroral processes and from the outer trapping region of the magnetosphere must be observed and included in simulations for an adequate treatment of mesospheric NO, the latter source of NO_y being significantly more important.

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