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Simulation of the October-November 2003 solar proton event in the CMAM GCM: comparison with observations

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The FTS instrument on SciSat-I observed a very large NO_x anomaly in mid February of 2004 near 80 N in the lower mesosphere. It has been proposed that the most likely origin of the lower mesosphere anomaly in February is transport, from the lower thermosphere or upper mesosphere, of high levels of NO_x associated with high levels of solar activity in Oct.-Nov. 2003. There was no major solar flare activity during January and February to cause ionization in the mesosphere. Using a middle atmosphere GCM we investigate whether the NO_x produced directly by the Oct.-Nov. 2003 solar flares or indirectly via enhanced auroral ionization as a result of magnetospheric precipitation can explain the ACE observations. We find that the solar proton events associated with the solar explosions in Oct.-Nov. 2003 produce insufficient amounts of NO_x in the mesosphere and thermosphere (less than 2 ppm at 90 km) to give rise to the observed anomaly. However, there is evidence that intense aurorae caused by the Oct.-Nov. 2003 solar storms produced thermospheric values of NO_x reaching hundreds of ppm. The NO_x created by the auroral particles appears to have lasted much longer than the immediate period of the Oct.-Nov. 2003 solar storms. It appears that NO_x rich air experienced confined polar night descent into the middle mesosphere during November and December, prior to the onset of the strong mesospheric vortex in January 2004.

1. Introduction

Observations by the FTS instrument on SciSat-I with the Atmospheric Chemistry Experiment (ACE) [*Rinsland et al.*, 2005] show a very large NO_x anomaly at NH polar latitudes during late winter and early spring of 2004. NO values of around 1.2 ppmv are found at 55 km and 80 N in the middle of February in 2004. The anomaly has a compact vertical distribution and descends at between 6 and 10 km per month, which is consistent with passive transport by the diabatic circulation. HALOE observes NO_x values of around 40 ppbv at 40 km and 71 N at the beginning of April [*Natarajan et al.*, 2004], which appear to be a remenant of the anomaly observed by ACE.

The origin of the NO_x anomaly is not clear. A suggested source is the October-November 2003 major solar proton events (SPEs) which resulted in ionization down to 30 km near the geomagnetic poles [*Jackman et al.*, 2004]. The period of the SPEs was preceded by record X-class X-ray flares and accompanied intense auroral activity. HALOE observed NO values over 100 ppmv around 100 km at 75 S in the first week of November, 2003 (data from haloedata.larc.nasa.gov). Since the photochemical lifetime of NO_x decreases rapidly with altitude any NO_x observed at 55 km, resulting from transport of air in the thermosphere or upper mesosphere, must have been confined to the polar night during the period of transport. *Randall et al.* [2005] argue that the unusually strong mesospheric winter polar vortex that developed by mid-January of 2004 and lasted well into February could have facilitated such confinement.

There appears not to have been sufficient M-class or higher X-ray flare activity following the solar flares in Oct.-Nov. 2003, which could directly generate large amounts of NO_x in the mesosphere (based on GOES observations, see rsd.gsfc.nasa.gov/goes and www.sec.noaa.gov/weekly, data also available from spidr.ngdc.noaa.gov/spidr) (We also note that X-ray ionization would not have been confined to auroral latitudes.) However, significant thermospheric NO_x production appears to have occurred after the SPEs as ACE finds values of NO over 10 ppmv at and above 90 km and 80 N in February, 2004. Due to the solar wind pressure from the coronal mass ejections (CMEs) associated with the Oct.-Nov. 2003 solar flares, the Van Allen belts were severely distorted during and after the CMEs so that highly energetic electrons (over 2 MeV) populated the innermost region ($L \leq 2$) [*Baker et al.*, 2004]. Intense auroral activity from these energetic electrons would have resulted in high levels of ionization reaching as low as the upper mesosphere (sec.noaa.gov/tiger).

The atmosphere was thus ionized through two separate, but related, sources connected with the solar activity of Oct.-Nov. 2003: 1) the high energy protons associated with the SPEs influenced the stratosphere and mesosphere; and 2) the energetic electrons associated with the aurorae from the magnetospheric disturbances and direct solar X-rays influenced the thermosphere and upper mesosphere. Here we present results from two simulations of these sources of atmospheric ionization with our Canadian Middle Atmospheric Model (CMAM). The first case is based on the ionization expected from high energy solar protons. Thus we have not included ionization from X-rays or precipitating magnetospheric particles. This ionization source does not produce the large NO_x values observed in the thermosphere, yielding NO_x mixing ratios which did not exceed 2 ppmv in the model thermosphere largely constrained by the upper boundary condition. Thus we include a second case with additional ionization in the thermosphere meant to mimic intense auroral activity accompanying the SPEs.

The CMAM has a spectral dynamical core with truncation set to T32. There are 65 sigma-pressure hybrid levels extending from the surface to between 90 km and 95 km. There is a non-zonal sponge layer in the upper two pressure scale heights of the model. A more detailed description is given by *Beagley et al.* [1997]. The CMAM has a comprehensive photochemical scheme [*de Grandpré et al.*, 1997, 2000] which can capture NO_x and HO_x production and decay. We take our initial state from an arbitrary model year well removed from spinup. CMAM has a reasonable mesospheric and stratospheric climate and we expect it to capture the main dynamical features relevant for NO_x transport. This approach is justified partly by the fact that no assimilation models produce data above 60 km. However, there are important limitations in that specific dynamical events are not reproduced. In particular, our simulations lack the exceptionally strong mesospheric polar vortex that developed during January and February of 2004 [*Manney et al.*, 2004].

2. Description of the Model Experiment

In this simulation we limit our ionization source to that due to direct injection of solar protons as measured by the GEOS-11 geostationary satellite. This satellite, of course, does not measure any input of particles from the magnetosphere. We have not included ionization from X-rays. NO_x and HO_x production rates were determined from the empirically derived energy deposition rate for the SPEs. The horizontal distribution of the energy deposition rate, E, was approximated by axially symmetric caps centered on the geomagnetic poles with a diameter of about 60 degrees (a smooth transition was assumed between 30 and 35 degrees from the poles). In cgs units the ionization rate, I, is given by

$$I = \frac{\rho E}{35.8 \times 10^{-6}} \tag{1}$$

where ρ is the air density. The production of HOx is given by

$$P_{HOx} = A(z)\, I \tag{2}$$

where $A(z)$ is given by *Solomon et al.* [1981]. It is assumed that P_{HOx} contributes equally to the production of H and OH. Following *Porter et al.* [1976] the production of NO_x is given by

$$P_{NOx} = 1.25\, I \tag{3}$$

and 45% of P_{NOx} is assumed to go towards ground state atomic nitrogen production while 55% is assumed to go into $N(^2D)$. The latter is added to the production of NO and O.

The CMAM simulation was initiated from a time before the SPEs and carried through until the end of March in the following year. A second run was performed which had the HO_x and NO_x production scaled by a factor of the form $1 + 99\ \exp(-((z - z_t)/8)^2)$ where z_t is the model lid height in log-pressure coordinate kilometers. This was intended to mimic an additional auroral source in the thermosphere during the SPEs. This scaling factor yielded only a factor of 30 increase of NO_x near 90 km (geopotential height), which is quite conservative. In addition to the two SPE cases there was a control run initialized from the same state.

3. Results

An altitude time series of the NH polar cap averaged (not area weighted) NO_y and passive NO-like tracer are shown in Figure 1 for the standard SPEs run. It is evident that there is a significant amount of photochemical destruction during the descent such that values near 1 ppmv do not appear in the lower mesosphere in February. As mentioned above, the highest values of NO_x produced during the SPEs do not exceed 2 ppmv and are found in the thermosphere. As indicated by the tracer time series this initial production is not sufficient to give observed values in the lower mesosphere via transport even if there is no photochemical loss. We also note that the total column NO_x production integrated over the period of the Oct.-Nov. SPEs is between a factor of 5 to 10 less than the column amount of excess NO_x found in the lower mesosphere in mid-February and this is with no allowance for photochemical loss. This fact in itself points to an additional NO_x source.

There is not enough confinement to the model polar night region to protect high NO_x values as they get transported to lower altitudes. This can be seen in Figure 2 which shows a latitude-time plot of zonally averaged tracer mixing ratio at 0.1 hPa. There is no sharp transition between mid-latitudes and the polar night, which follows from the fact that the tracer experiences significant horizontal quasi-reversible transport towards mid-latitudes. It is also evident that there are periods when the tracer values in the polar night are no larger than in the sunlit latitudes. During these periods the horizontal tracer distribution is distributed over a large area with no identifiable polar core region (not shown).

However, there is agreement between the model results in November and December with GOMOS observations [*Seppälä et al.*, 2004] of NO_2 in the stratosphere. Figure 3 shows vertical profiles of NO_2 zonally averaged at 75 N and time averaged over 10 day periods from before the SPEs until late December. These profiles are similar to those shown in Figure 2 of *Seppälä et al.* [2004]. Descent of NO_2 produced during the SPEs in the upper stratosphere is evident. During this period the observed polar vortex was not abnormally disturbed in the stratosphere as well as in CMAM. In addition, at these altitudes the photochemical lifetime of NO_x is much longer than in the mesosphere. Under these conditions the differences between model and observations are tied to the diabatic circulation and the initial NO_x production. The model does well in both regards. The change in NO_2 around 30 km as winter solstice is approached is reduced in the enhanced SPEs case, which corresponds to the absence of such evolution seen in the GOMOS profiles.

The results for the run with additional thermospheric NO_x production are shown in Figure 4. Once again there is very little NO_x that survives transport from the thermosphere into the lower mesosphere. This is consistent with the lack of long term isolation of the descending air mass in the polar night in CMAM. The NO-like tracer distribution indicates that high thermospheric or upper mesospheric values of NO_x could explain the over 1 ppmv observed in February of 2004 if polar night vortex isolation were to occur. However, there is a significant amount of vortex disruption in the mesosphere as can be seen in Figure 5.

The ozone responses for each of the standard SPEs and the enhanced SPEs cases are shown in Figure 6. Even though there is essentially no difference between the two cases in terms of ionization below 65 km, there is more NO_y transported into the middle stratosphere in the enhanced case and subsequently more ozone loss at these altitudes. The ozone loss seen in the enhanced SPEs case is similar to that seen by GOMOS during November and December 2003 (cf Figure 1 of *Seppälä et al.* [2004]).

Nonlinearity appears have amplified the small initial differences in the radiative state of the two SPEs cases which stem from differences in ozone loss above 65 km. The stratospheric vortex in the enhanced SPEs case is less disturbed as evidenced by the larger values of NO in Figure 4 (b) compared to Figure 1 (b) during December and January and the lack of positive ozone differences in Figure 6 (b) in the stratosphere during this time. It is this increased isolation that leads to higher values of NO reaching lower altitudes since the differences in the NO production below 65 km are negligible. More NO_y implies less ozone which appears to strengthen the vortex. Work to understand this bifurcation in the coupling between ozone loss and dynamics is in progress and will be reported elsewhere.

Large monthly mean zonal wind differences (not shown) of up to 40 m/s appear from December through March. The winter polar vortex in the model experienced a major warming and began to breakdown in the middle of February in the enhanced SPEs case. It did not recover in March. This appears as the large positive change in ozone in stratosphere (lower panel of Figure 6). For the standard SPEs case the polar vortex was still intact in March.

4. Discussion

The model simulations presented here fail to reproduce observed NO levels in the lower polar mesosphere both because the descending polar air mass experiences significant horizontal disturbances on a regular basis which bring it into regions of daylight and also because the NO source appears insufficient. The disturbances which are likely due to gravity and Rossby waves resolved by the model also disrupt the polar air mass and prevent the formation of a core that is confined to the polar night for a sufficient duration. The state of the CMAM mesosphere has reasonable agreement with the observed climatology. However, the 2003-2004 winter was highly atypical with strong mesospheric westerlies developing by mid-January and persisting into mid-February [*Manney et al.*, 2004].

Under typical conditions, the mesospheric polar vortex is weak [*Fleming et al.*, 1988] and can be readily perturbed by large scale waves. The wave-driven diabatic circulation produces rapid descent in the high latitude winter mesosphere and the associated dynamical heating reverses the meridional temperature gradient. As a result the westerlies originating in the stratosphere are attenuated in the mesosphere.

The mesospheric diabatic circulation is governed primarily by gravity wave drag. If the zonal flow in the stratosphere is westerly then gravity waves with westerly zonal phases are filtered out at critical lines such that mostly easterly phase gravity waves reach the mesosphere and produce easterly drag [*Holton*, 1982]. Similarly, the sign of mesospheric gravity wave drag reverses when the zonal flow becomes easterly in the stratosphere. Strong westerlies in the stratosphere give rise to strong easterly gravity wave drag in the mesosphere, which drives a stronger poleward diabatic circulation. Conversely, stratospheric warmings cause mesospheric cooling by reducing easterly gravity wave drag. Major warmings lead to the development of westerly drag when stratospheric winds reverse. This westerly drag reverses the zonal flow and the diabatic circulation in the lower thermosphere and upper mesosphere [*Liu and Roble*, 2002].

Based on the above, it is likely that the upper mesosphere and lower thermosphere winter polar region was experiencing ascent in January and February of 2004 during the unusual major warming which persisted for over four weeks. The descent at lower mesospheric altitudes inside the strong polar vortex was also weaker. The ACE NO measurements appear to be consistent with this view since for about a week after February 15, 2004, there is very little descent of the anomaly. As the stratospheric westerlies recover by late February and the mesospheric westerlies weaken the descent increases to about 6 km/month. The slow descent inside the mesospheric vortex puts a limit on how much transport can be achieved. The anomalously strong vortex only lasted about a month during which time it is unlikely that there was more than 6 km of descent in the middle and lower mesosphere. So high values of NO_x must have been present at middle mesospheric altitudes (around 60 km) before the formation of the strong vortex in mid-January 2004.

Although there is little direct information available concerning the circulation in the upper mesosphere from the middle of November 2003 into January of 2004, it does appear that high values of NO_x were transported to middle mesosphere altitudes during this time from the lower thermosphere or upper mesosphere. The HALOE observations in the southern hemisphere polar region, which would also have experienced ionization by solar flares during the first week of November, give a constraint on the vertical distribution of NO_x that formed in the northern hemisphere. Taking into account the opposite sign of the upwelling in polar region of both hemispheres, there could have been over 100 ppmv of NO_x around 90 km in the northern hemisphere in early November 2003, but not at much lower altitudes. Absent other sources at later times, NO_x produced in the lower thermosphere in November was the source of the lower mesosphere NO_x anomaly in February 2004. This requires that the mesospheric winter polar vortex was much less disturbed than was the case in our GMAM simulations from mid-November to early January so that NO_x remained in the dark.

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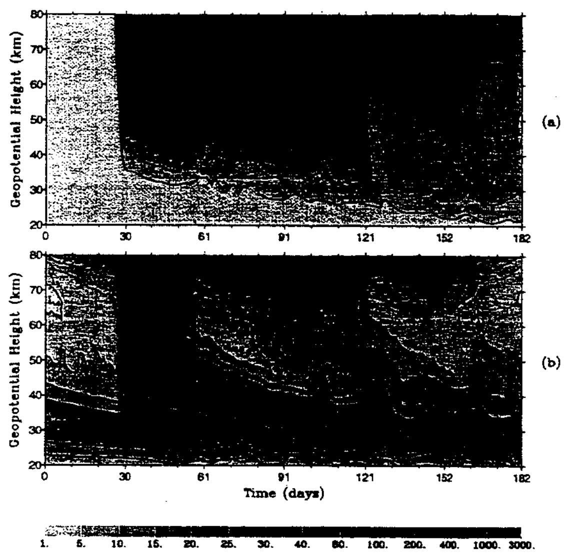

Figure 1. (a) 75 N - 90 N average of NO-like tracer vs. time for the standard SPEs run (ppbv). (b) Same as (a) but for NOy.

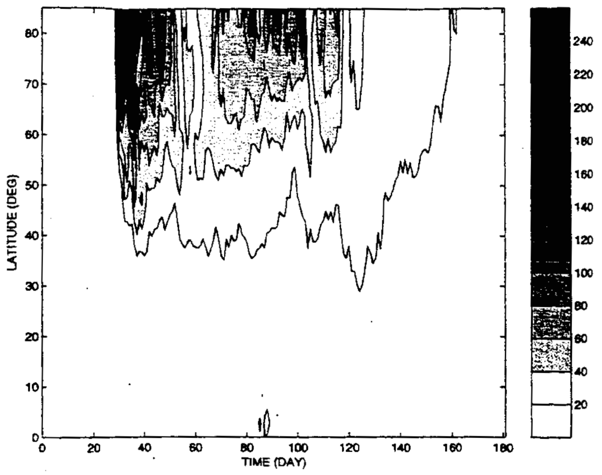

Figure 2. Zonal mean NO-like tracer at 0.1 hPa vs. time for the standard SPEs run (ppbv).

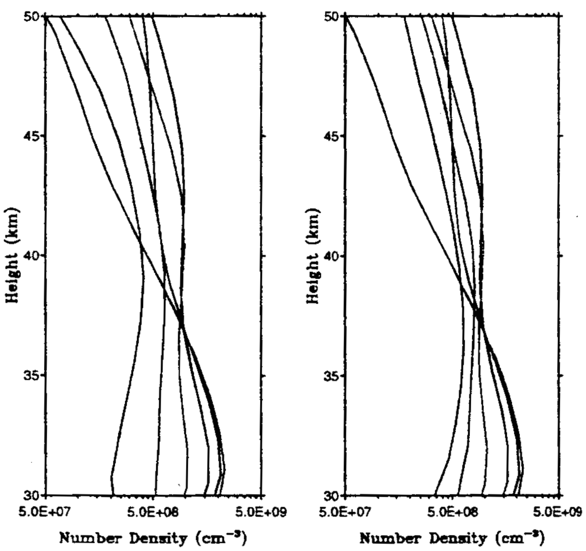

Figure 3. Ten day average profiles of NO_2 averaged over the 70 N - 75 N polar ring. Results for the standard SPEs run are in the left panel, results for the enhanced SPEs case are shown in the right panel. Black corresponds to Julian days 291-300, green to 301-310, blue to 311-320, teal to 321-330, purple to 331-340 and red to 341-350.

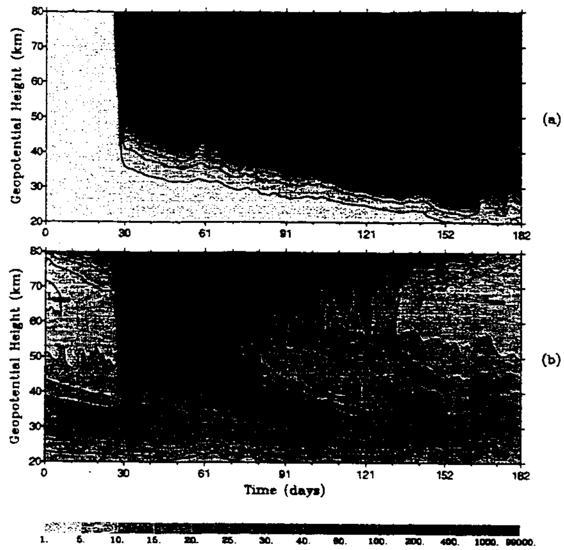

Figure 4. (a) 75 N - 90 N average of NO-like tracer vs. time for the SPEs run with enhanced ionization in the thermosphere (ppbv). (b) Same as (a) but for NOy.

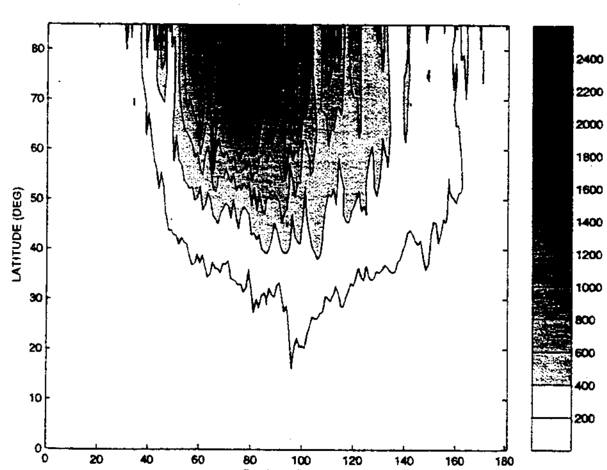

Figure 5. Same as Figure 2 but for the SPEs run with enhanced ionization in the thermosphere.

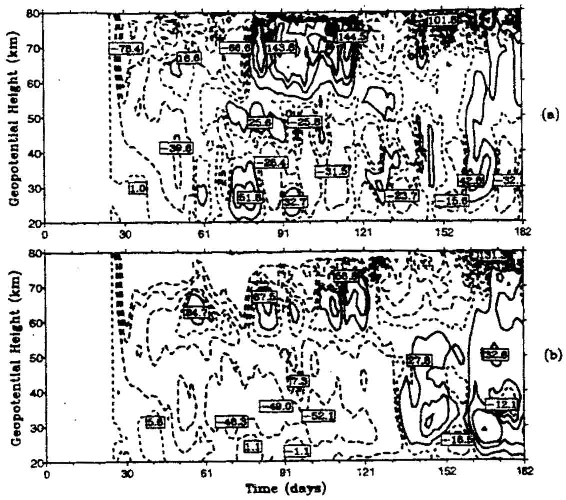

Figure 6. Percentage difference of 75 N - 90 N average ozone from the reference run for (a) standard SPEs case and (b) enhanced SPEs case. Contour levels are -100, -50, -30, -10 (dash), 0 (short dash), 10, 30, 50, 100 (solid). A 1-2-1 filter has been applied along the time axis.

Simulation of the October-November 2003 solar proton event in the CMAM GCM: comparison with observations

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Brief, Popular Summary of the Paper:

Very large upper stratospheric NOx (NO + NO2) enhancements were measured by the Fourier Transform Spectrometer (FTS) instrument aboard the Canadian SciSat-I in February 2004 at high northern latitudes. It was postulated that the extremely large solar proton events, which occurred in October-November 2003, may have produced this anomaly. Solar proton events create nitrogen-containing compounds, which can lead to ozone destruction in the mesosphere and upper stratosphere. The fourth largest period of events in the past 40 years occurred in October 28-31, 2003. Other solar proton events occurred in early November, 2003.

The Canadian Middle Atmosphere Model (CMAM) General Circulation Model (GCM) was used to investigate the possibility that the October-November 2003 solar proton events may have caused the huge measured NOx enhancements in February 2004. The proton events in late 2003 were computed to have caused significant changes in polar mesospheric and stratospheric NOx for several weeks past the events, however, these impacts did not last until February 2004.

The CMAM GCM was then used to simulate a possible impact from auroral particles, which are primarily electrons. It was discovered that the NOx rich air from the thermosphere, produced by the auroral particles, could have been transported through the mesosphere and into the upper stratosphere in December and January. This large-scale transport was possible because there was relatively little dilution in late 2003 and early 2004 from the middle latitudes of the huge polar NOx amounts.