NOx descent in the Arctic middle atmosphere in early 2009

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[1] Measurements by the Atmospheric Chemistry Experiment show that the amount of NOx (NO + NO2) produced by energetic particle precipitation (EPP) that descended from the Arctic mesosphere and lower thermosphere into the stratosphere in early 2009 was up to ~50 times higher than average in 2005, 2007 and 2008. This is of note because the level of EPP in the preceding months was very low, suggesting that excess production of NOx was not the cause of the enhancements. Rather, the enhancements are attributed to unusually strong descent in the middle atmosphere. This is the third time on record that extraordinary meteorology contributed to descent of excess NOx. The results confirm that EPP impacts on the middle atmosphere can be large even in the absence of exceptional EPP, and highlight the need to continually measure NOx throughout the polar region from the stratosphere to the lower thermosphere. 


1. Introduction

[2] Energetic Particle Precipitation (EPP) refers to the process by which energetic electrons and protons impinge on the Earth’s atmosphere. One consequence of EPP is production of NOx (NO + NO2) in the mesosphere and lower thermosphere (MLT), and occasionally in the stratosphere. NOx has a lifetime of days to weeks in the mesosphere, with longest lifetimes in the polar winter. If dynamical conditions are favorable, the NOx produced by EPP (hereafter referred to as EPP-NOx) can thus be transported downward into the stratosphere during the polar winter. This process is referred to as the EPP indirect effect (EPP IE) [Randall et al., 2007]. Once in the stratosphere, EPP-NOx has a lifetime on the order of months or longer, and catalytically destroys O3.

[3] Observational evidence for the EPP IE has been given by a number of authors [e.g., Funke et al., 2005; Jackman et al., 2008; Siskind et al., 2000; Randall et al., 1998, 2001, 2007]. Randall et al. [2007] showed that interannual variability in the southern hemisphere (SH) EPP IE correlates very well with the level of EPP itself. They suggested that this was due to the fact that interannual variability in SH dynamics is small, so interannual variability in the EPP IE is controlled primarily by changes in EPP-NOx production, not transport. In the northern hemisphere (NH), however, dynamical variability is high, so the EPP IE does not correlate well with variations in the production of EPP-NOx as inferred from the Ap index or EPP hemispheric power. The purpose of this paper is to describe observations that show that for the second time in four years, unprecedented meteorological conditions led to very large amounts of descending EPP-NOx in the NH, even though the level of EPP was well below average. This result is significant in that it confirms that the production of EPP-NOx is potentially an important element in O3 depletion regardless of the level of geomagnetic activity, and that EPP influences can often be enhanced by favorable serendipity between space weather and meteorology.

2. Results

[4] Figure 1 compares NOx descending from the MLT during the Arctic winters from 2004–2009. NOx mixing ratios are from the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) solar occultation instrument [Bernath et al., 2005; see also Sica et al., 2008]. ACE-FTS only samples a single latitude on any given day, which is shown in Figure 1 (top); measurement latitudes nearly repeat from year to year. Figure 1 shows prominent tongues of NOx descending from the MLT into the Arctic stratosphere in 2004, 2006, and 2009. Because the only significant source of MLT NOx at the ACE latitudes in winter is EPP, these tongues can unambiguously be identified as EPP-NOx.

[5] The Arctic EPP IE in 2004 was larger than ever before observed in either the NH or SH; NOx mixing ratios at 40 km were up to a factor of 4 higher than nominal at some locations [Randall et al., 2005]. Unusual meteorology was a key factor in these enhancements, including a remarkable vortex recovery after a mid-winter sudden stratospheric warming (SSW) and enhanced adiabatic descent in the mesosphere [Hauchecorne et al., 2007; Jin et al., 2005; Manney et al., 2005, 2008a]. Exceptional EPP levels in Oct–Dec 2003 have also been suggested as contributing, although Clilverd et al. [2006] concluded that this was not necessary. Extraordinary meteorology once again prevailed during the Arctic 2006 winter, and was responsible for the tongue of descending NOx in the MLT that is so prominent in Figure 1 for that year [Manney et al., 2008a, 2008b; Randall et al., 2006; Siskind et al., 2007]. There was only minimal geomagnetic activity in late 2005 and early 2006:
Auroral power was well below the average since 1978, the geomagnetic Ap index was lower than it had been since 1988, and there was no evidence of enhanced fluxes of high energy protons or relativistic electrons. Thus, unlike in 2004, the late winter/spring NOx enhancements of 2006 were more clearly attributed to the dynamical situation.

Measurements of the 2008–2009 Arctic winter show that for the third time in six years, polar winter meteorology was remarkably different from the norm prior to 2004. Manney et al. [2009] describe a major SSW in January 2009 that was the strongest and most prolonged on record; upon recovery, the stratopause reformed in early February at 80°C from an altitude of 80 km, which is arguably more typical of a mesopause altitude than a stratopause altitude. The response of the MLT to such a remarkable warming includes enhanced descent in the polar MLT, and thus transport of EPP-NOx down toward the stratosphere. This is obvious in Figure 1 (bottom), which shows the prominent "tongue" contours until early March confirms that NOx is indeed descending. In early March photochemistry begins to perturb both CO and NOx, resulting, e.g., in the sharp decrease in NOx near 70 km. In the Arctic in 2004, 2006, and 2009, the 2.0 ppmv CO contour reached altitudes as low as 45–50 km in early Mar. In all other winters, in either hemisphere, it never reached lower than ~60 km, consistent with less descent in these winters.

Figure 2 quantifies the amount of EPP-NOx reaching an altitude of 55 km in the Arctic winters of 2004–2009 by correlating CH4 and NOx; an anti-correlation is indicative of descending EPP-NOx [e.g., Randall et al., 2007; Siskind and Russell, 1996]. Much more EPP-NOx reaches 55 km in 2004, 2006, and 2009 than in 2005, 2007, or 2008, with highest NOx corresponding to lowest CH4, indicating that it descended from higher altitudes. Although not shown, NH EPP-NOx mixing ratios at 55 km range from 2 to 20 (10) times higher in 2004, 2006, and 2009 than the highest NOx mixing ratios observed in other years in the NH (SH) back to 1992. Figure 2 also shows the relationship between CO and CH4 at 55 km. In the absence of mixing, these tracers should show a tight correlation, with minimum (maximum) values of CH4 (CO) indicating the highest originating altitude. Maximum CO mixing ratios in 2004, 2006, and 2009 are nearly 3–6 times higher than maximum CO mixing ratios in 2005, 2007, and 2008, indicating much more descent in the mesosphere. This is consistent with the conclusions of Winick et al. [2009], who inferred enhanced descent in the mesosphere in 2004 and 2006 based on analysis of mesospheric OH airglow observations. The tighter correlation in 2004 indicates less mixing, which might partially explain the higher 2004 NOx values in the top panels.
Manney et al. (2009) noted that planetary and gravity waves can lead to unusual meteorological conditions in the middle atmosphere, and by implication, dynamical fields. Siskind et al. (2009) showed little evidence of the EPP IE at 45 km in 2009, other than in the polar region – is the same characteristic that prevents the SH from exhibiting exceptionally large EPP-NOx mixing ratio enhancements such as seen in 2004, 2006, and 2009.

Figure 3. Ratio of NOx in 2004, 2006, and 2009 to the average NOx observed in years 2005, 2007, and 2008, calculated from the data in Figure 1. For guidance, dotted vertical lines indicate 1 Feb and 1 Mar. White diamonds indicate the altitude of the stratopause at the ACE locations.

3. Discussion and Summary

The 2004 and 2006 winters have already been linked to unusual meteorological conditions in the middle atmosphere, specifically with regard to the propagation of planetary and gravity waves (Hauchecorne et al., 2007; Manney et al., 2008a, 2008b; Sathishkumar and Sritharan, 2009; Siskind et al., 2007; Winick et al., 2009). A complete discussion of the 2009 meteorology is beyond the scope of this paper; however, Manney et al. (2009) have already pointed out certain similarities, such as an unusually strong and persistent SSW that occurred in January and was followed by the reformation of a strong upper stratospheric vortex and displaced (elevated in altitude) stratopause. One difference was that the 2006 SSW was primarily dominated by a planetary wave 1, whereas the 2009 event was dominated by wave 2. Here we highlight how key features in the descending NOx are linked to key features in the temperature, and by implication, dynamical fields.

Superimposed on the NOx enhancements in Figure 3 is the zonal average stratopause height, inferred from temperature maxima measured by ACE between 15 and 90 km. The polar winter stratopause height is typically near 50 km; Figure 3 shows that in these three years, the stratopause height at the ACE measurement latitudes reached well above this altitude, to ~75 km in 2009, indicative of enhanced descent in the mesosphere. The onset of NOx enhancements coincided with formation of the displaced stratopause in both 2006 and 2009. Because of the lack of ACE NOx measurements prior to 21 Feb 2004, it is impossible to draw conclusions for that year. Nevertheless, the data are strongly suggestive of similar behavior in 2004; temperatures from the Sounding of the Atmosphere using Broadband Radiometry (SABER) indicate stratopause heights as high as 80 km by mid-Jan in 2004 (not shown). Year 2006 shows a strongly displaced stratopause in early Feb that then drops back to ~50 km before becoming displaced again; accordingly, NOx enhancements appear first in early Feb near 70–80 km, before dissipating and then appearing consistently from mid-Feb onward. Similar behavior occurs in 2009, although it is not as dramatic. Thus the evidence is compelling that the NOx enhancements were caused by increased descent. Finally, it is not surprising that such large EPP-NOx enhancements have not yet been observed in the SH, since recovery from major SSWs, which are not known to occur in the middle of SH winters, apparently triggered the enhanced descent in the NH MLT. It is ironic, in fact, that the characteristic that makes the SH favorable for the EPP IE – a generally strong and stable vortex that promotes confinement of EPP-NOx in the polar region – is the same characteristic that prevents the SH from exhibiting exceptionally large EPP-NOx mixing ratio enhancements such as seen in 2004, 2006, and 2009.

To summarize, we have shown that 2009 was the second year on record, 2006 being the first, in which exceptional meteorology in the Arctic stratosphere and MLT led to significant descent of EPP-NOx in the polar region, even though geomagnetic activity was significantly lower than average. Thus the extraordinary EPP effects on the atmosphere in 2006 were not a one-time occurrence. Similar meteorology was observed in 2004, but was preceded by large solar storms in late 2003. Of these three years, and at the ACE measurement locations, EPP-NOx enhancements were largest in 2004; enhancements were larger in 2009 than in 2006 above about 60 km, but descended farther in 2006 than in 2009. Significant effects on O3 are not expected (nor observed) in 2009 because the NOx mixing ratios did not increase substantially at the altitudes where NOx is most effective at catalytic O3 destruction, from about 22–45 km.

It is important to note the limitations on these conclusions, however, which include the lack of data in the polar night, daily varying and sparse latitude sampling, and the lack of high-latitude data from late March to early May. As an indication of these limitations, Figure 4 shows Arctic 2009 temperatures from the SABER instrument. Note the substantial differences in character between the different latitude bands. As shown in Figure 1, ACE measurement latitudes vary by ~30 degrees from early Jan through Mar, and thus do not always correspond to the most extreme temperatures in the polar region. For example, in early Feb ACE is sampling ~65°N, where there is no indication of a displaced stratopause; at 80–85°N in early Feb, however,
stratopause had already started to reform near 80 km. ACE thus does not sample locations with the most extreme meteorological conditions. In addition, ACE measurements are not made in the polar region in April, when descending NOx is most likely to reach altitudes where it is the main catalyst of O3 destruction; for instance, the April 2004 O3 depletions of up to 60% that were observed by HALOE [Randall et al., 2005] were not seen by ACE. These limitations emphasize the need for continual measurements of NOx throughout the polar region, from the stratosphere to the lower thermosphere.

[14] The observation of so much descending MLT NOx in both 2006 and 2009, when EPP was at very low levels, supports the suggestion of Clilverd et al. [2006] that the late winter/spring NOx enhancements that led to the extraordinary O3 losses in 2004 were in fact not connected to the solar storms of 2003. Instead, they were more likely due primarily to the unusual meteorology, with a contribution from moderate levels of EPP in Jan-Feb 2004. Further research is necessary to determine in detail the differences in EPP-NOx production and atmospheric meteorology that led to the different magnitudes of the observed EPP IE in the three years, and to understand whether the unusual meteorology can be linked to a specific cause.

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Figure 4. Zonal mean SABER temperatures from 10 Jan to 12 Mar in 2009, in the latitude bands given in each plot. Vertical dotted lines denote 1 Feb and 1 Mar. Black dots denote the stratopause, defined as the maximum temperature from 15–100 km.